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CANADIAN RURAL POWER QUALITY ANALYSIS

by

Haizhen Wang

A thesis submitted to the faculty of Graduate Studies and Research in partial fulfillment of the requirement for the degree of Master of Science

Department of Electrical and Computer Engineering

Edmonton, Alberta

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ABSTRACT

This thesis presents the analysis of the rural power quality data based on the CEA survey and defines the Canadian rural electrical environment. Rural power quality is an increasing concern as the proliferation of the computer-like equipment in the rural area. This thesis has investigated the long-term steady-state voltage levels of rural sites and whether the feeder length affected the voltage levels at the rural sites or not. The statistical characteristics of rural voltage disturbances and distributions of their magnitude and duration, respectively, were analyzed to reveal distinctive patterns of occurrences. Finally, the Canadian rural group power quality profile has been summarized. The contour lines of voltage sags, swells and surges have been drawn and their compliance with the ITI curve has been checked. The study enables a better understanding of the Canadian rural electrical environment and provides a knowledge base for utilities and rural customer to choose mitigation measures.

AKNOWLEDGMENT

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LIST OF NOMENCLATURE AND ABBREVIATIONS

PQ: power quality

CEA: Canadian Electrical Association

CEBMA: the Computer Business and Equipment Manufacturers Association

ITI: the Information Technology Industry Council

CSA: the Canadian Standard Association

UPS: Uninterrupted Power Supply

BMI: Basic Measuring Instrument

PLC: Programmable Logic Controller

ITE: Information Technology Equipment

AC: Alternated Current

THD: Total Harmonic Distortion

Chapter 1 Introduction

This chapter will provide an introduction to the subject area of power quality. The classifications of power supply disturbances and anomalies are presented and discussed. This chapter ends with a statement of the thesis objective and scope of the work.

1.1 Power Quality

Power quality is a relatively obscure concept. The term *quality* is sometimes used as synonymous with supply reliability [1] to indicate the existence of an adequate and secure power supply. A broader definition [2] has described *service quality*, encompassing the three aspects of reliability of supply, quality of power offered and provision of information. *Power quality* is generally used to express any power problem manifested in voltage, current or frequency deviation that results in the failure or malfunction of customer equipment [3]. With the expansion of power electronic control in the transmission and utilization of electrical energy, there is an increasing acceptability of the latter interpretation.

Power quality is a two-pronged issue. There is large growth in the use of electronic loads that can be disrupted by power supply disturbances. At the same time there is large growth in the use of power electronic devices which generate power supply disturbances. Business and industry normal operations are also becoming increasingly dependent on

the performance of their electrical and electronic equipment. All these factors considered together are expected to lead to increased power quality problems in the future.

A power quality (PQ) survey captures the characteristics of PQ disturbances and identifies the current PQ level in certain areas. It also provides a basis for mitigating actions by utilities and their customers to design and operate their electrical systems to minimize the effects of power supply disturbances. Many power quality surveys were carried out in the 90's. Among them are the Canadian Electrical Association (CEA) National Power Quality Survey [4] and the Electric Power Research Institute (EPRI) Power Quality Survey [5]. Between 1990 and 1995, EPRI took a survey on PQ levels across continental United States in which twenty-four utilities participated. Since the EPRI survey results were not widely published, few results are available for research. The CEA survey will be introduced and analyzed in this thesis.

Network based power quality monitoring systems are emerging. For example, the I-Grid system is one of the innovative, web-based distributed power quality and reliability monitoring and notification systems. I-Grid uses ultra-low cost I-Sense™ monitors to capture and transmit power data through the Internet to a central server for display on the I-Grid website, as well as send event notification to individual monitored sites. Due to the security issue, the author could not get access to the details of the commercial power quality data recorded by I-Grid. A comparison with the CEA rural power quality survey results was not possible.

1.2 Power Disturbances

Despite disagreements on what constitutes electric power quality, there is a concerted call to establish a common description of the power quality phenomena and the environment in which they occur. The two most widely referenced standards or guidelines are the International Electrotechnical Commission (IEC) Electromagnetic Compatibility (EMC) Standard series and the IEEE 1159 [7]. Table 1-1 shows the IEEE categorization of electromagnetic phenomena used for the power quality community.

Table 1-1 Categories and characteristics of power system electromagnetic phenomena

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1. Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5 ns rise	< 50 ns	
1.1.2 Microsecond	1 μs rise	50 ns – 1 ms	
1.1.3 Millisecond	0.1 ms rise	> 1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	< 5 kHz	0.3 – 50 ms	0 – 4 p.u.
1.2.2 Medium frequency	5 – 500 kHz	20 μs	0 – 8 p.u.
1.2.3 High frequency	0.5 – 5 MHz	5 μs	0 – 4 p.u.
2. Short-duration variations			
2.1 Instantaneous			
2.1.1 Interruption		0.5 – 30 cycles	< 0.1 p.u.
2.1.2 Sag (Dip)		0.5 – 30 cycles	0.1 – 0.9 p.u.

Table 1-1 (continued)

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
2.1.3 Swell		0.5 – 30 cycles	1.1 – 1.8 p.u.
2.2 Momentary			
2.2.1 Interruption		30 cycles – 3 s	< 0.1 p.u.
2.2.2 Sag (Dip)		30 cycles – 3 s	0.1 – 0.9 p.u.
2.2.3 Swell		30 cycles – 3 s	1.1 – 1.4 p.u.
2.3 Temporary			
2.3.1 Interruption		3 s – 1 min	< 0.1 p.u.
2.3.2 Sag (Dip)		3 s – 1 min	0.1 – 0.9 p.u.
2.3.3 Swell		3 s – 1 min	1.1 – 1.2 p.u.
3. Long-duration variation			
3.1 Interruption		> 1 min	0.0 p.u.
3.2 Undervoltages		> 1 min	0.8 – 0.9 p.u.
3.3 Overvoltages		> 1 min	1.1 – 1.2 p.u.
4. Voltage unbalance		Steady state	0.5 – 2%
5. Waveform distortion			
5.1 DC offset		Steady state	0 – 0.1%
5.2 Harmonics	0 – 100th harmonic	Steady state	0 – 20%
5.3 Interharmonics	0 – 6 kHz	Steady state	0 – 2%
5.4 Notching		Steady state	
5.5 Noise	Broadband	Steady state	0 – 1%
6. Voltage fluctuation	< 25 kHz	Intermittent	0.1 – 7%
7. Power freq. Variations		< 10 s	

Among the power disturbances, voltage sags, voltage swells and transients/surges are the common concerns for utilities and their industrial & commercial customers. Table 1-2 illustrates the origins and impact of voltage sags, voltage swells and surges on electronic & electrical equipment [17, 18].

Table 1-2 Causes and Effects of PQ Disturbances on Electronic & Electrical Equipment

Disturbances	Typical Causes	Effects on Electronics & Electrical Equipment
Sags and Swells	Utility faults, motor starting, lightning strikes	Computer system interruptions, motor stalling
Transients	Lighting, load, Capacitor-bank switching	System overvoltages which cause insulation failures, malfunction of sensitive electronic devices
Harmonic Distortion	Power Electronics, arcing device, saturable device	Capacitor blowing, transformer heating/failures, breaker nuisance trips, protective relaying errors

The typical waveforms of sample voltage sags, voltage swells and voltage surges are shown in Figure 1-1, Figure 1-2, Figure 1-3 and Figure 1-4.

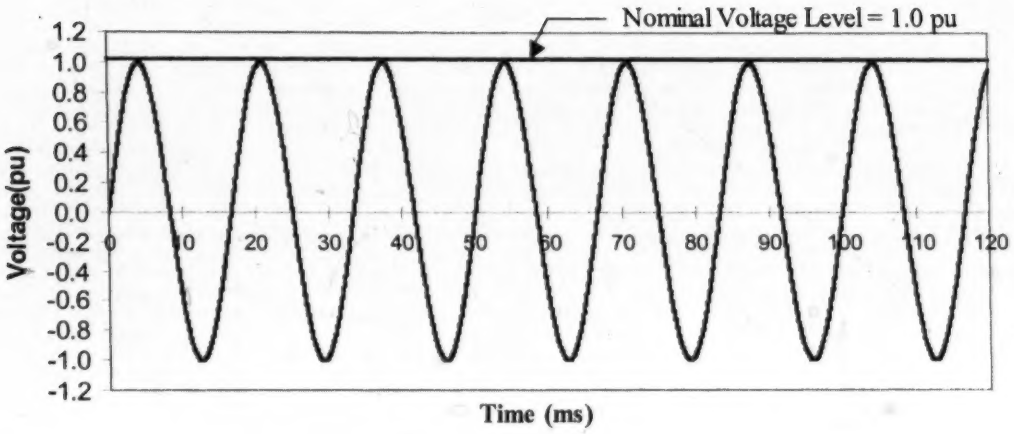


Figure 1-1 Nominal Voltage Waveform

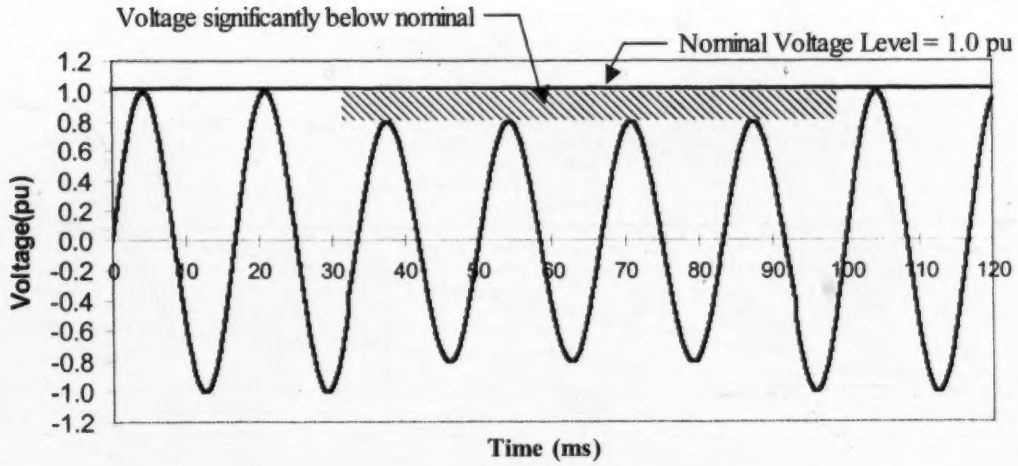


Figure 1-2 Sample Waveform of a Voltage Sag

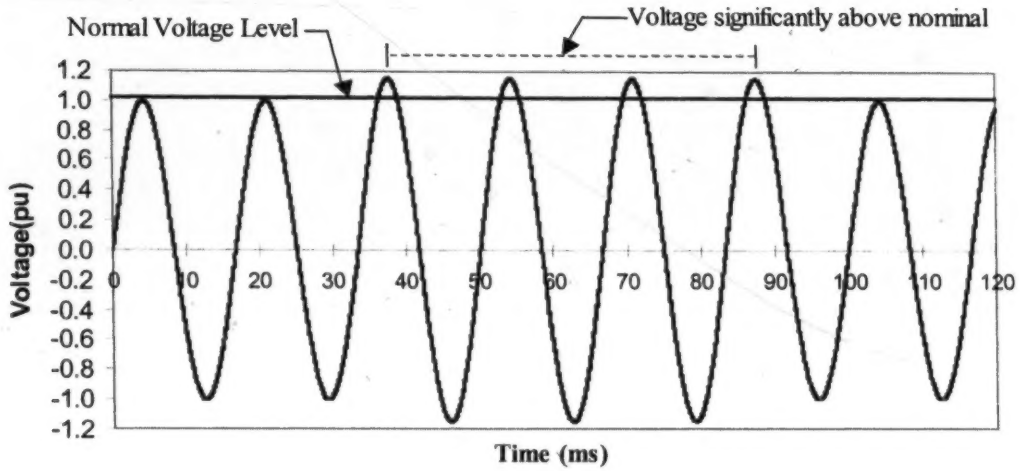


Figure 1-3 Sample Waveform of a Voltage Swell

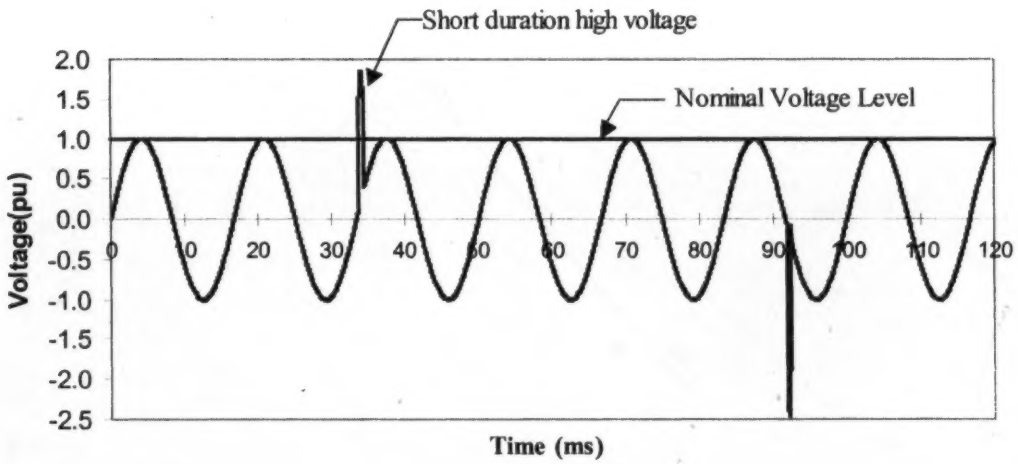


Figure 1-4 Sample Waveform of a Voltage Surge (Transients)

Power Quality disturbances are customarily eliminated or mitigated by power conditioning equipment such as isolation transformers, surge suppressers, Uninterrupted Power Supply (UPS) and voltage regulators [8]. However, it should be noted that although power conditioning can deal with the PQ problem to a certain extent, their installation causes economic losses for the customer in view of up front energy losses ranging from 10-20% [9]. Current PQ disturbance mitigation techniques include provision of a dedicated line, separate regulating transformers for sensitive loads, surge suppressor, etc.

1.3 CEA National Power Quality Survey on Rural Sites

In 1991, the CEA launched a proactive 3-year power quality survey. There were 22 investor owned utilities participating in the survey and 550 sites monitored. Among them 69 sites were rural. The frequency of rural voltage sags has been reported in Reference [11]. However, the rural data has not been thoroughly studied. Voltage profiles and other statistical characteristics of the CEA rural data will be presented in this thesis.

1.3.1 CEA PQ Survey measure protocol

Basic Measuring Instrument (BMI) power line level monitors were chosen to measure transient disturbances and steady-state voltage. Both two-channel BMI 2460's and four-channel BMI 4800's were used. In order to be able to compare the data gathered at different sites, the following measurement protocol was followed in the CEA PQ Survey:

- Monitor at the 120/240 Volt, 120/208Volt secondary level.
- Monitor at the service entrance panel. (Monitoring at the distribution feeder voltage level would probably not show customer generated disturbances. Monitoring further into the customers premises could make the results highly susceptible to loads on an individual circuit.)
- Monitor phase-neutral voltage only. Neutral and ground should be the same at the service entrance panel.
- Monitor each site for approximately one month.
- Monitor an even sampling of industrial, commercial and residential customers.

Four kinds of power quality disturbances were detected and recorded: voltage sags, voltage swells, voltage surges, and voltage waveshape faults. In addition, outages were recorded in the CEA survey. Actually outages are voltage sags of zero volts lasting more than 10 seconds. The monitor threshold levels used in the CEA PQ Survey are listed in the following Table 1-3.

Table 1-3 Monitor Threshold Setting

Disturbance Type	Voltage Threshold	Duration
Surge	>150 V peak	<1 msec
Waveshape Fault	>25 V peak change	>0.1 cycle (1.6 msec)
Sag	<110 Vrms	80 msec – 10 sec
Swell	>125 Vrms	80 msec – 10 sec

It can be noted that there is a disturbance type labeled "waveshape fault". According to IEEE Std. 1159-1995, the shorter duration waveshape faults (1ms-8.3ms) can be reclassified into the disturbance type called "Transients". The remaining disturbances can be grouped into the type called "Short Duration Variations (voltage sags and swells)". In addition to this difference, there are also other minor deviations from the IEEE recommended classifications, which could affect the interruption of the survey results based on today's terminology.

Figure 1-5 shows the power disturbances graphically, superimposed on the CEBMA power quality envelope [6].

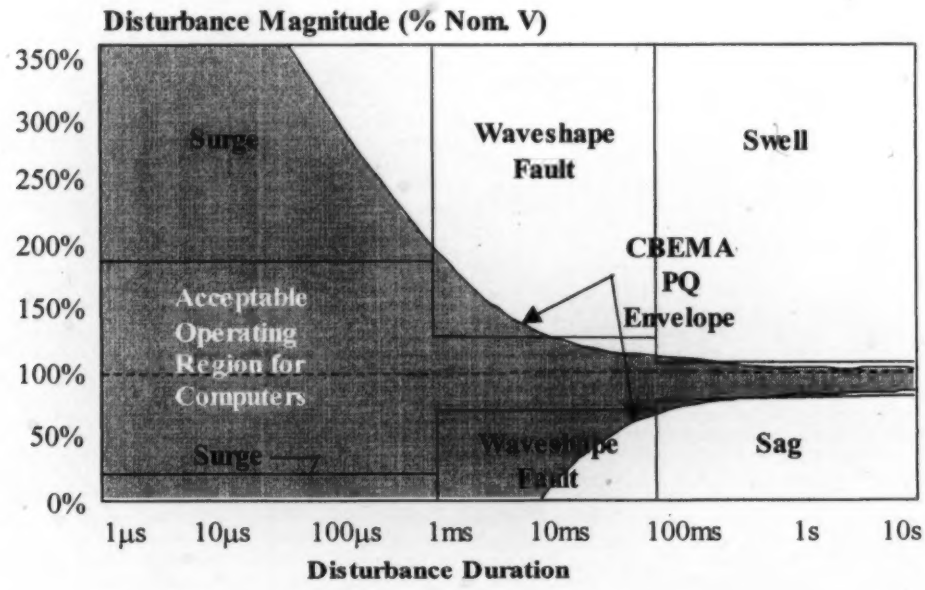


Figure 1-5 Monitor Settings & CEBMA PQ Envelope

The electric power susceptibility curves are an empirical set of curves that represent the intensity and duration of bus voltage disturbances [14]. Power susceptibility curves are used to assess the power supply quality. CBEMA or ITI curve is the best-known electric power susceptibility curve.

The Computer Business and Equipment Manufacturers Association (CBEMA) curve was established in 1978 as a first attempt to determine the appropriate response of computer equipment to undervoltage conditions (sags and interruptions) and overvoltage conditions (swells). In 1995, EPRI research on computer power supplies led to a revised CBEMA curve known as CBEMA 96 or the Information Technology Industry Council (ITI) curve [13].

The ITI (CBEMA) Curve and its Application Note describe an AC input voltage envelope which typically can be tolerated (no interruption in function) by most Information Technology Equipment (ITE). The Curve and its Application Note comprise a single document and are not to be considered separately from each other. They are not intended to serve as a design specification for products or AC distribution systems. The Curve and the Application Note describe both steady state and transitory conditions. It is available at http://www.itic.org/technical/iticurv.pdf.

Figure 1-6 shows the ITI power quality envelope [15]. The ITI (CBEMA) curve is a susceptibility profile. The vertical axis of the graph is the magnitude of the voltage disturbances that applied to the power circuit in percentage of nominal voltage, and the

horizontal axis is the duration of the voltage disturbances involved in microseconds to seconds. In the center of the chart is an acceptable area, and on the outside of that area is a danger area on top and bottom. The danger zone (Prohibited Region) at the top involves tolerance of equipment to excessive voltage levels. The danger zone (No Damage Region) on the bottom sets the tolerance of the equipment to a loss or reduction in applied voltage. If ITE is subjected to disturbances that are in the Prohibited Region, damage to the ITE may result. If the disturbances are in the No Damage Region, the normal functional state of the ITE is not typically expected, but no damage to the ITE should result.

The ITI curve will be used to access the severity of voltage disturbances experienced at the rural sites in the CEA PQ Survey. For instance, a voltage sag with a drop of 80% in magnitude and 0.6s duration may result in ITE function interruption. A voltage surge with 250% magnitude and 1ms duration may cause damage to ITE.

The disturbances at individual sites will be plotted together with the ITI curve to check for compliance. The contour lines of rural group voltage disturbances will also be compared with the ITI curve to access the rural power quality environment.

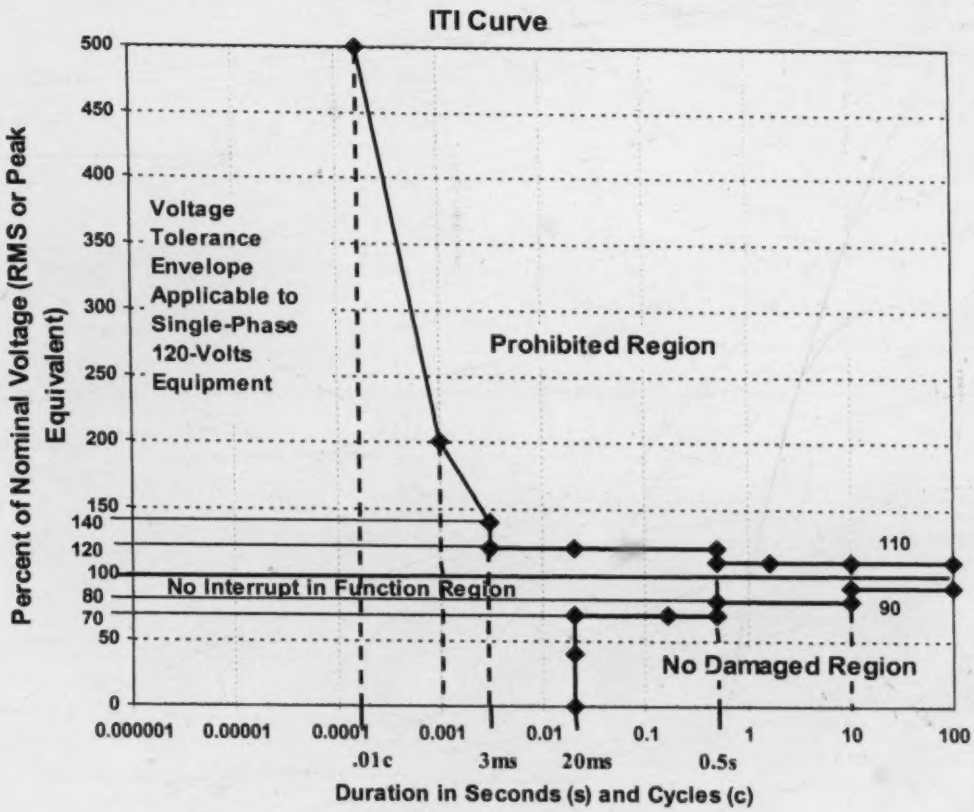


Figure 1-6 the ITI Curve

1.3.2 CEA PQ Survey Data Presentation

In the CEA survey, the magnitude and duration of the voltage sags, voltage swells, waveshape faults and voltage surges are derived as follows.

- Voltage sags & swells – BMI monitor records the maximal voltage reached and the total time the voltage exceeded the sag or swell threshold levels. Figure 1-7 and Figure 1-8 show the magnitude and duration of the typical voltage sag and voltage swell respectively. An outage is a special kind of voltage sag. The magnitude and duration of the typical outage is shown in Figure 1-9.

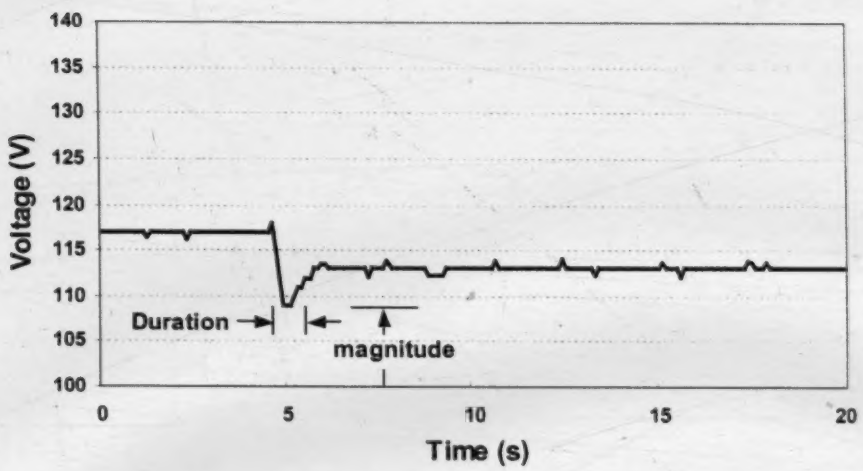


Figure 1-7 Magnitude and Duration of a Voltage Sag (109V, 0.9s)

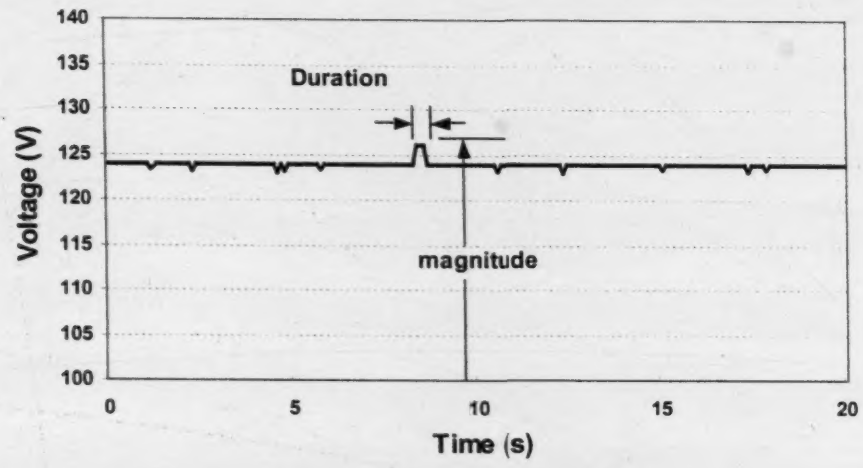


Figure 1-8 Magnitude and Duration of a Voltage Swell (127V, 0.5s)

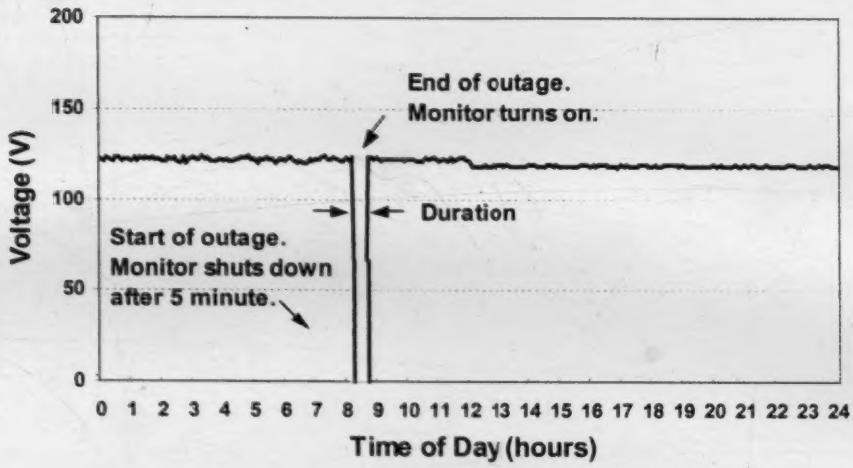


Figure 1-9 Magnitude and Duration of an Outage (0V, 20minutes)

- Voltage surges – Surge waveform is recorded with the 60 Hz fundamental stripped off, as shown in Figure 1-10. The peak surge voltage, the surge phase position on the

60 Hz fundamental waveform, and the estimated energy content are also reported. The surge magnitude is the peak voltage reached, and the surge duration is the time taken for the equivalent surge to rise to its peak and then decay to half of its peak value. The equivalent surge is calculated based on the double-exponential waveform used for surge testing [10].

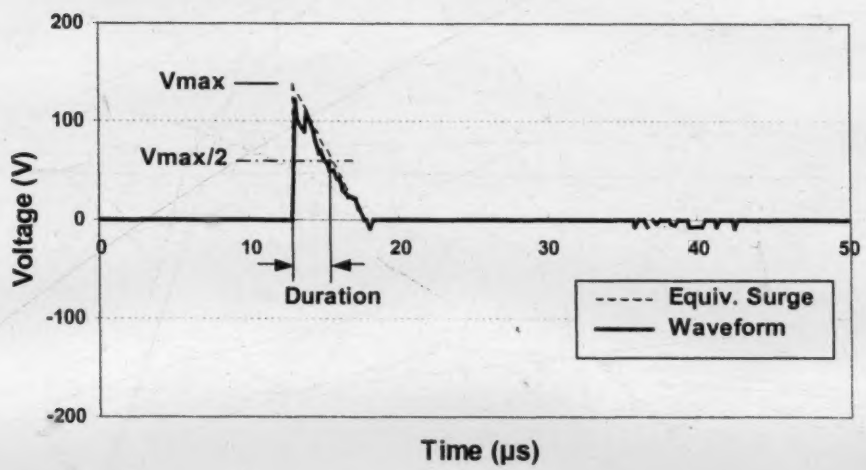


Figure 1-10 Magnitude and Duration of a Voltage Surge (145Vpeak, 2µs)

- Waveshape faults – if there is a voltage waveform difference exceeding 25 volts peak for more than 0.1 cycle duration when comparing the present cycle versus the previous cycle, a waveshape fault is reported. The waveshape fault duration is the time interval between the start and end times. The waveshape fault magnitude is calculated as the RMS voltage value of the recorded waveform between the start and end times. If the waveshape fault is too short to allow an RMS calculation to be done,

the peak voltage deviation is used as the magnitude. The magnitude and duration of the typical outage is shown in Figure 1-11.

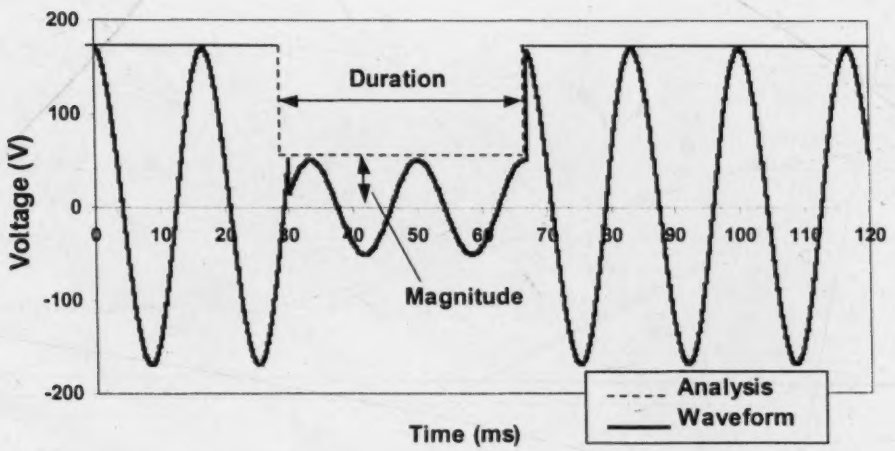


Figure 1-11 Magnitude and Duration of a Waveshape fault (56V, 37ms)

1.4 Scope of the work

With the proliferation and use of computers in society, there is a growing concern of power quality problem for the rural customer [11]. However, a literature review revealed there is a limited number of power quality surveys conducted specifically for rural electrical systems [12]. The CEA PQ Survey data of rural sites will be systematically analyzed and presented in this project. The main objectives of this project are:

- Provide rural customers with information on the quality of their electric power supply;
- Provide a data base for economical mitigation actions;
- Provide empirical evidence of utility performance;
- Provide a means of assessing the impact of rural customer polluting loads on their own power quality.

1.4.1 Steady-state voltage profile of the CEA rural power quality data

The long-term steady-state voltage profiles of the rural sites are plotted as the voltage histograms superimposed by the voltage level limits from the CAN-C235-83 Standard, "preferred voltage levels for AC systems, 0-50,000V" [24] which is made by the Canadian Standard Association. The histogram shows not only the voltage level at the rural site in a month but also the percentage of time when the voltage level was in "Normal operating conditions" or "Extreme conditions" as defined by CAN-C235-83.

The minimum, maximum and average/expected voltage level at each rural site in the CEA survey are calculated and plotted in figures separately. The minimum and maximum voltage levels, and the average voltage at rural sites during the monitored period are presented.

1.4.2 Some statistical characteristics of the CEA rural voltage disturbances

The power disturbances recorded in the CEA rural power quality survey are statistically analyzed. The patterns of occurrence (i.e., time in a day, day in a week) of voltage sags, swells and surges are presented and discussed. The distribution of magnitude and duration of these voltage anomalies are presented to build an empirical knowledge base of the rural electric environment in Canada. These statistical characteristics will provide a guide for designing rural electric equipment and choosing mitigation techniques.

1.4.3 Define the rural electric environment based on the CEA survey

Rural power disturbances are summarized as a group. The rural group long-term steady-state voltage profile has been derived weighted by the actual site monitoring duration. All rural group voltage disturbances are summed with a scale factor, then girded and gray-scaled according to the event exposure in each grid. The compliance of voltage sags, voltage swells and voltage disturbances with the ITI curve is examined. Power quality profile of rural sites is compared with the other sites (Industrial, Commercial, Residential) in the CEA Survey. The electric environment of the Canadian rural area is defined.

Chapter 2 CEA Rural Steady State Voltage

The purpose of this chapter is to define the rural long-term steady state voltage levels based on the CEA Power Quality Survey data. Standard CAN3-C235-83 is introduced and used to qualify service entrance and the utilization voltage levels at rural sites. Finally, the rural voltage supply waveform distortion characteristic will be summarized.

2.1 CEA Rural Steady State Voltage

The distribution of electrical energy to the rural community is subject to various regulations. In this chapter, the CSA standard CAN3-C235-83 ("Preferred Voltage Levels for AC Systems, 0 to 50,000V") is used. It specifies the upper and lower voltage level at a customer's service entrance. Service voltage operating outside these limits can significantly affect the performance of rural electronic and electrical equipment.

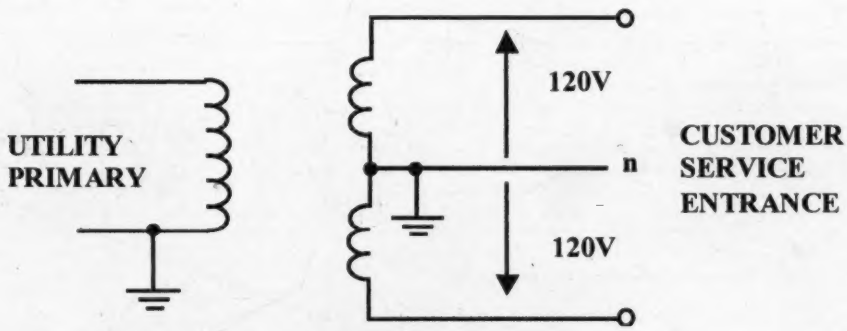


Figure 2-1Single Phase Service Entrance

According to CAN3-C235-83, the recommended voltage variation limits for AC systems single-phase 120V at the service entrance is shown in the Figure 2-2. The monitored rural sites are all single-phase 120V systems as illustrated in Figure 2-1.

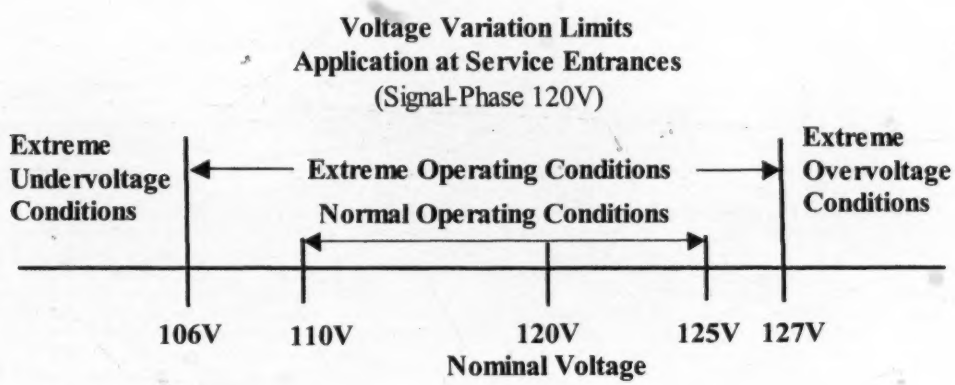


Figure 2-2 Recommended Voltage Variation Limits for circuits up to 1000V, at Service Entrance

A single diagram of a typical customer's electric power supply system is shown in the following Figure 2-3. A step down transformer changes the high distribution line voltage into the utilization voltage used by the customer (i.e. 120V nominal voltage for single phase and 120/208V for three phases customers). The power quality meters are installed on the secondary side of the step down transformer, at the service entrance in the CEA survey. A feeder cable connects the utilization point to the service entrance. Usually there is a 2V-voltage drop along it. In other words, the voltage at the service entrance is typically 2 volts higher than that of the utilization point. This can be verified through the

difference between the low and extreme low voltage limits in the CAN3-C235-83 Standard.

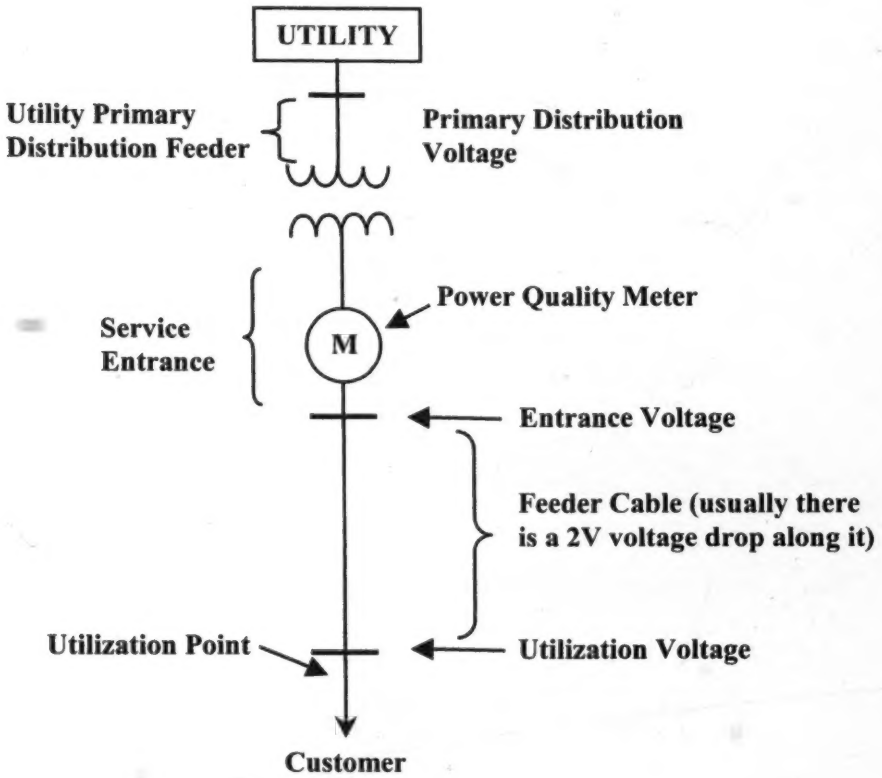


Figure 2-3 One-line Diagram of a Customer Electric Power System

According to CAN3-C235-83, the recommended voltage variation limits for AC systems single-phase 120V at the utilization point are shown in the Figure 2-3. Compared to the Figure 2-2, the voltage limits are all 2 volts lower.

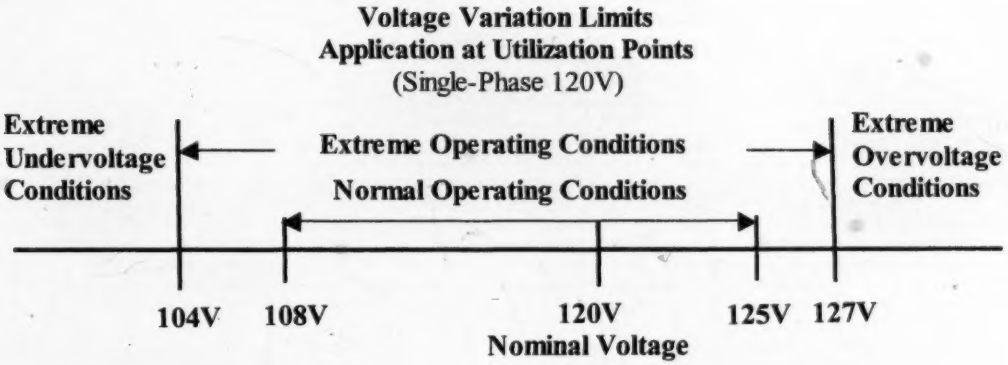


Figure 2-4 Recommended Voltage Variation Limits for circuits up to 1000V, at Utilization Points

The voltage histogram is plotted for each rural site to compactly show its steady-state voltage levels during one month of monitoring. The percentage of voltage levels falling into the five voltage categories are calculated and listed in tables. The five voltage categories are defined as follows: extreme low (108V~110V), low (110V~120V), normal (120V), high (120V~125V), and extreme high (125V~127V).

The utilization point voltage can be assumed to be 2 volts less than the service entrance voltage. The utilization point voltage histogram is also plotted for each rural site and compared with the voltage limits in the Figure 2-4.

The voltage histograms show how the long-term steady-state voltage levels at rural sites clustered around the nominal voltage. At some sites, the voltage levels appeared to be

normal (the normal operating conditions) while others the voltage levels were significantly either higher or lower than the nominal voltage. The voltage histograms of three sites were selected and are shown in Figures 2-5 to 2-10.

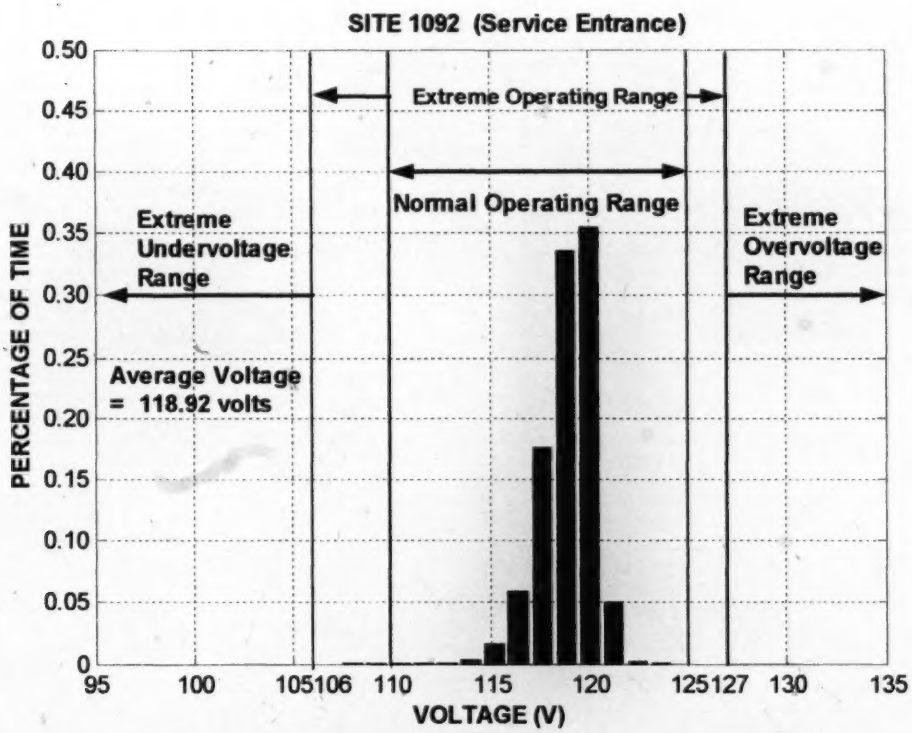


Figure 2-5 Site 1092 Voltage Histogram at the Service Entrance

The service entrance voltage histogram of the Site 1092 is plotted in the above Figure 2-5. "Extreme Low Voltage", "Normal Voltage", and "Extreme High Voltage" ranges are defined according to the CAN3-C235-83 Standard and indicated in the figure. With reference to Figure 2-5, the voltage levels of Site 1092 were mostly (99.98% of the total

monitoring time) within in the normal operating conditions. Only during 0.02% of the total time the voltage was in the extreme low operating conditions.

Figure 2-6 shows the utilization point voltage histogram of the Site 1092 as follows: "Extreme Low Voltage", "Normal Voltage", and "Extreme High Voltage" ranges. These are also defined according to the CAN3-C235-83 Standard and indicated in the figure. Observed from Figure 2-6, though the voltage level of Site 1092 was in the normal operating conditions for the majority of the time monitored, it was lower than the nominal voltage 120V.

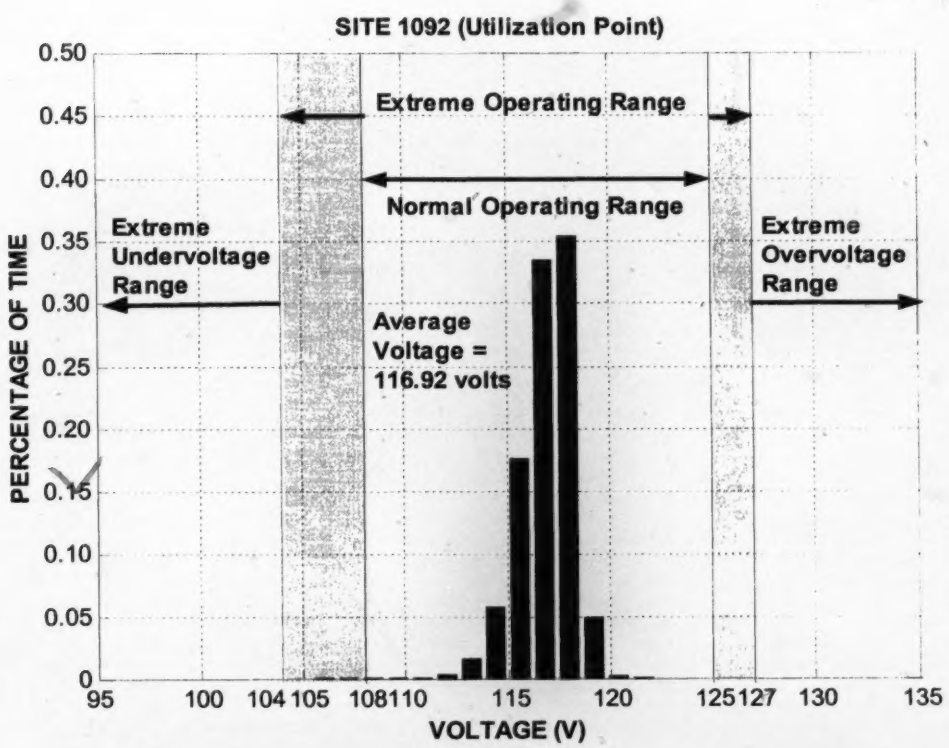


Figure 2-6 Site 1092 Voltage Histogram at the Utilization Point

Comparing the percentages of voltage in different ranges at the service entrance and utilization point at Site 1092, we can see that the percent of time when voltage was within the normal operating range but below the nominal voltage level increased at the utility point than that of service entrance. Within the extreme low/high voltage ranges, the percentages of time are the same at the service entrance and utility point, which is shown in Table 2-2.

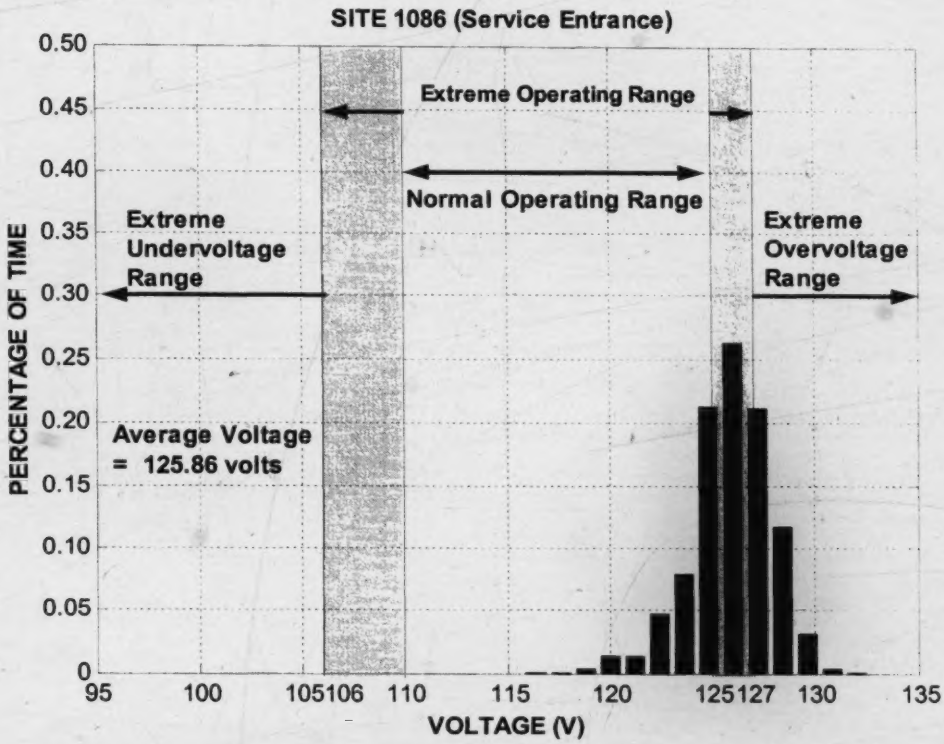


Figure 2-7 Site 1086 Voltage Histogram at the Service Entrance

The service entrance voltage histogram of the Site 1086 is plotted in Figure 2-7. With reference to Figure 2-7, the voltage level of Site 1086 was extremely higher than the

nominal voltage. Only 37.29% of time the voltage level was within the normal operating voltage range. Most of the time (62.71%) the voltage level was in the extreme operating condition range. 565 voltage swells were captured at Site 1086.

The utilization point voltage histogram of the Site 1086 is plotted in Figure 2-8. It can be observed from Figure 2-8 the utilization voltage level of Site 1086 was not so high as that at the service entrance. During the 63.52% (37.29% at the customer service) of the total monitored time the site voltage level was within the normal operating condition voltage range.

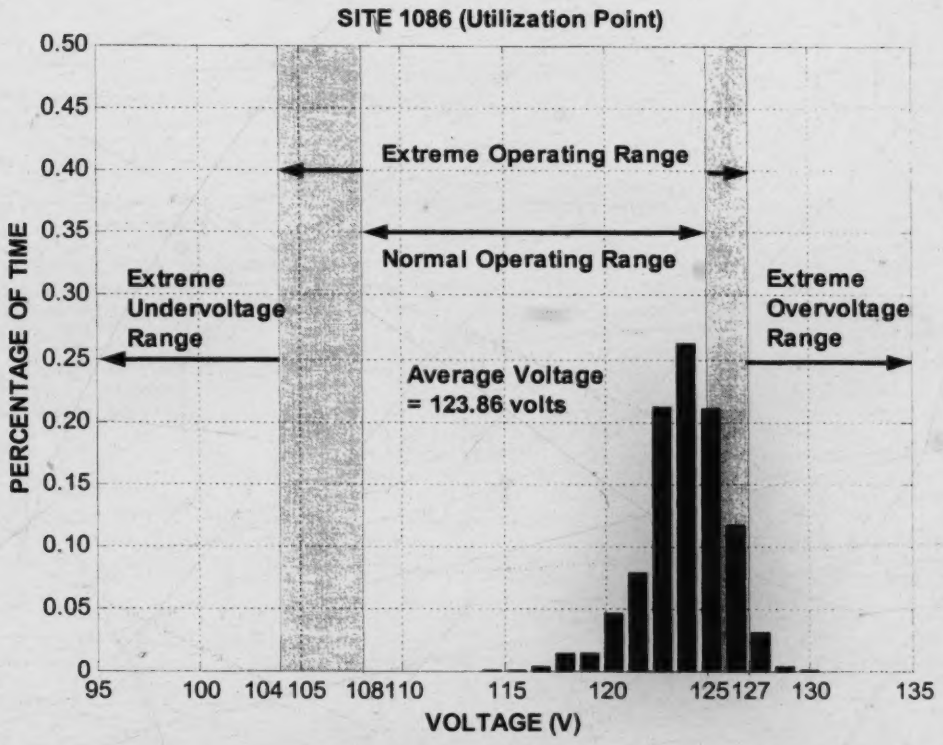


Figure 2-8 Site 1086 Voltage Histogram at the Utilization Point

The service entrance histogram of the Site 1080 is plotted in Figure 2-9. With reference to Figure 2-9, the voltage level of Site 1080 was distributed almost evenly in the normal operating voltage range. 37.29% of time the voltage level was in the extreme operating condition range. The minimal voltage at Site 1080 was 96V. 792 voltage sags were captured at Site 1080. Its low voltage level may relate to the loose neutral at the site.

The comparison of percentage of time when site voltage was in different ranges at service entrance and utilization point will be presented in Table 2-2.

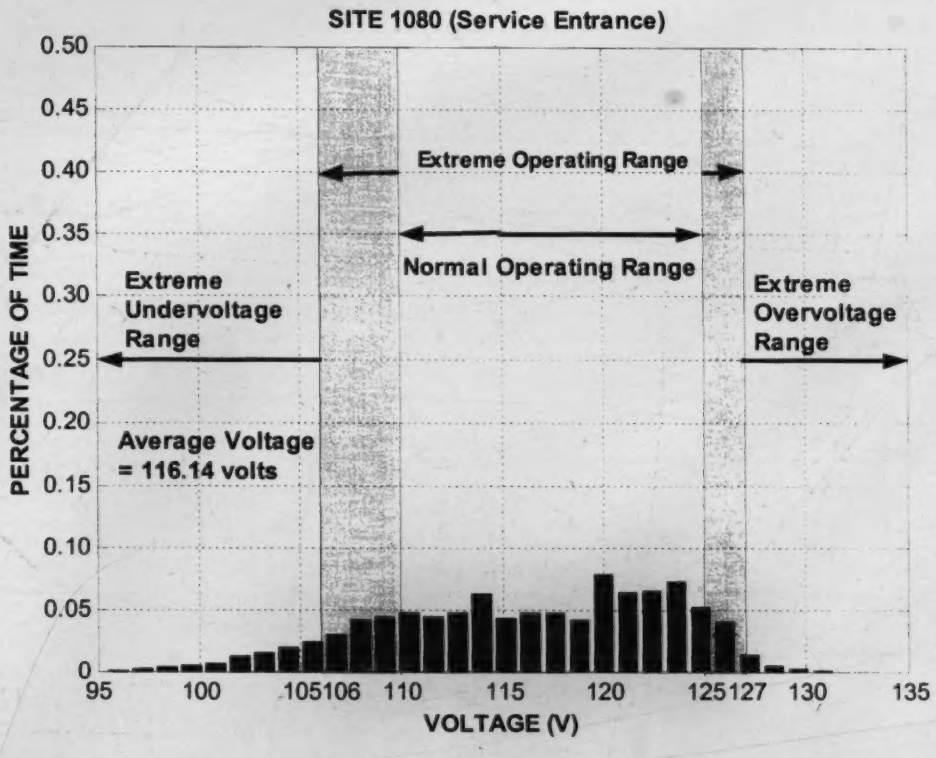


Figure 2-9 Site 1080 Voltage Histogram at the Service Entrance

The utilization point histogram of the Site 1080 is plotted in the following Figure 2-10. It can be seen from Figure 2-10 that the voltage level of Site 1080 was distributed through all the voltage ranges. The utilization voltage level was in the extreme low operating range in 20.78% of the total monitored time, just the same as at the service entrance. However, the utilization voltage level was in the extreme high operating voltage range dropped to 2.09% instead of 6.21%.

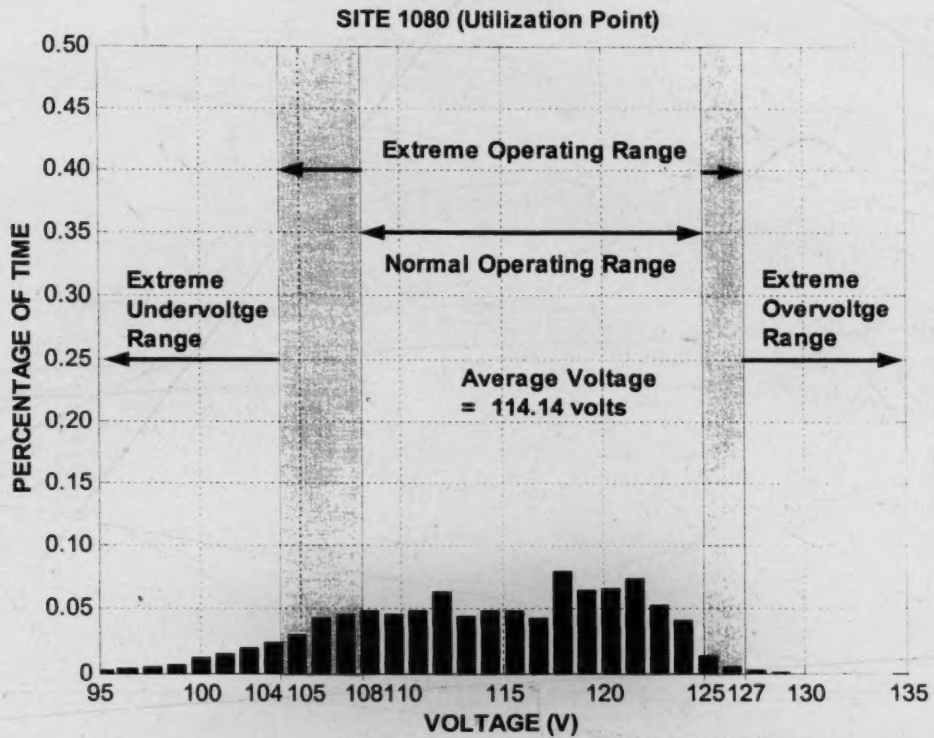


Figure 2-10 Site 1080 Voltage Histogram at the Utilization Point

Table 2-1 and Table 2-2 show the minimum, maximum and average, and the percentage of time when voltage level within the five different voltage ranges of the above three sites as follows.

Table 2-1. Min, Max & Average Values of Rural Site Voltage

Site Name	Minimal Voltage (V)	Maximum Voltage (V)	Average Voltage (V)
SITE1092	108.00	123.60	118.92
SITE1086	116.40	132.00	125.86
SITE1080	96.00	130.80	116.14

Table 2-2. Voltage Range of Rural Site

		← Extreme Operating Range				→
			← Normal Operating Range →			
Monitor Site	**Site Name**	**Extreme Low (%)**	**Low Voltage (%)**	**Normal (%)**	**High (%)**	**Extreme High (%)**
Service Entrance	SITE1092	0.02	59.23	35.39	5.36	0.00
	SITE1086	0.00	0.53	1.32	35.44	26.22
	SITE1080	11.92	39.12	7.95	7.95	25.93
Utilization Level	SITE1092	0.02	99.67	0.26	0.05	0.00
	SITE1086	0.00	3.29	4.80	55.43	32.87
	SITE1080	11.92	53.59	6.72	16.81	1.78

The percentage of time when the service entrance and utility point voltage was in different voltage ranges has been presented in Table 2-2. The percentage of time that the voltage resides within each of the voltage ranges is unique for each site.

One common thing is that the percent of time when voltage was in the extreme low range was the same at both the service entrance and the utilization point at a specific site because the utility point voltage dropped 2 volts compared to the service entrance so did the utilization point voltage extreme low range limits.

Another character is that utilization point voltage shifted down 2 volts. As a result, the percentage of time when voltage was in the normal operating conditions increased at the utilization point, especially in the normal operating but below the nominal voltage range.

The percentage of time when voltage was within the extreme high range usually decreased at the utilization point compared to that of the service entrance. Exceptional case appears when the site voltage was very high. For example, Site 1080 had voltage that exceeded the extreme high voltage limit at the service entrance. After voltage dropped down 2 volts at the utilization point, the percentage when voltage was still within the extreme high range.

2.2 CEA Rural Minimum, Maximum & Average Voltage

The voltage histograms of the individual rural site at the service entrance and utilization point are studied in the section 2.1. To get a general picture of all the rural sites the minimum, maximum and average voltage level at the service entrance for each site has been extracted, ordered and plotted in the following figures.

Figure 2-11 shows the minimal voltage level at the service entrance of each rural site. The horizontal axis is the number of rural sites. Actually, it is the order of the minimum voltage of sites.

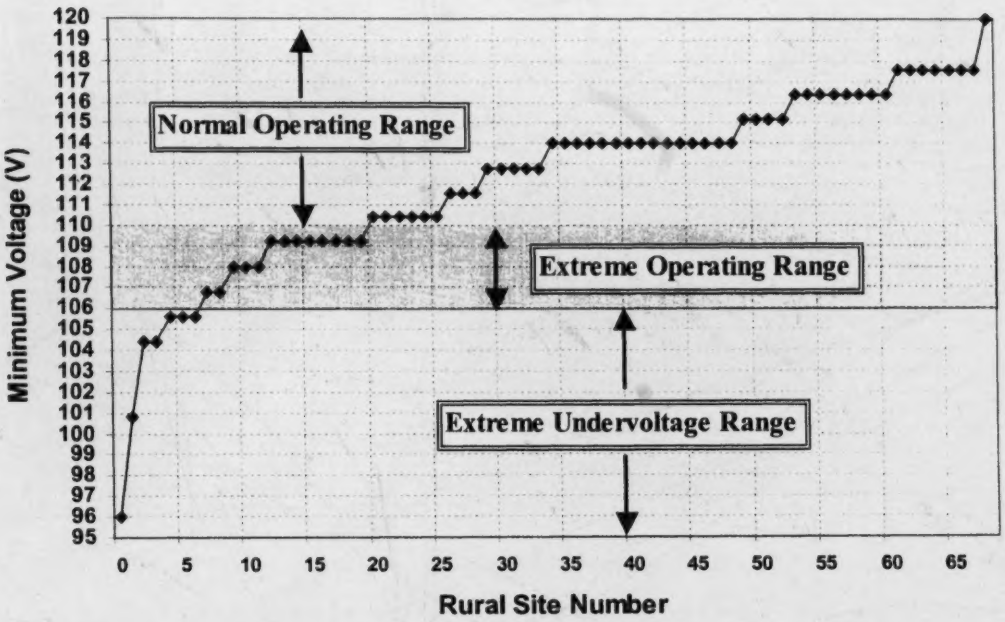


Figure 2-11 Minimum Voltage Level at Each Rural Site (Service Entrance)

Observed from Figure 2-11, only one site (Site 1080) has the minimum voltage under 100V. There are 20 sites that have the minimum voltage under 110V within the extreme low operating range. 114V was the most common minimum voltage level. 15 out of 69 sites had the minimum voltage level of 114V. The highest minimum voltage level was 120V at Site 0543. Checking the average voltage level at Site 0543, it was 127.54V. The voltage at this site was not extremely high. The voltage level quite centered around the nominal voltage.

Table 2-3 shows the correspondence between the CEA rural Site ID and its corresponding site number labeled in Figure 2-11.

Table 2-3. CEA Site ID & Corresponding Number for the Minimal Voltage Plot

CEA Site ID	Number	CEA Site ID	Number	CEA Site ID	Number
SITE1080	1	SITE0288	24	SITE0103	47
SITE0037	2	SITE0169	25	SITE0091	48
SITE0488	3	SITE0064	26	SITE0034	49
SITE0235	4	SITE0539	27	SITE0425	50
SITE0479	5	SITE0398	28	SITE0272	51
SITE0454	6	SITE0056	29	SITE0218	52
SITE0432	7	SITE0423	30	SITE0168	53
SITE0234	8	SITE0329	31	SITE1086	54
SITE0073	9	SITE0112	32	SITE0515	55
SITE1092	10	SITE0052	33	SITE0478	56
SITE0523	11	SITE0015	34	SITE0459	57
SITE0175	12	SITE1018	35	SITE0443	58
SITE1042	13	SITE0616	36	SITE0424	59
SITE0399	14	SITE0600	37	SITE0324	60
SITE0213	15	SITE0446	38	SITE0278	61
SITE0166	16	SITE0444	39	SITE0535	62
SITE0148	17	SITE0438	40	SITE0437	63
SITE0128	18	SITE0433	41	SITE0428	64
SITE0124	19	SITE0411	42	SITE0285	65
SITE0082	20	SITE0298	43	SITE0282	66
SITE1083	21	SITE0281	44	SITE0206	67
SITE0488	22	SITE0168	45	SITE0423	68
SITE0459	23	SITE0112	46	SITE0128	69

Figure 2-12 shows the maximum voltage level at each rural site. The horizontal axis is the number of rural sites, which is actually the descending order of the maximum voltage levels.

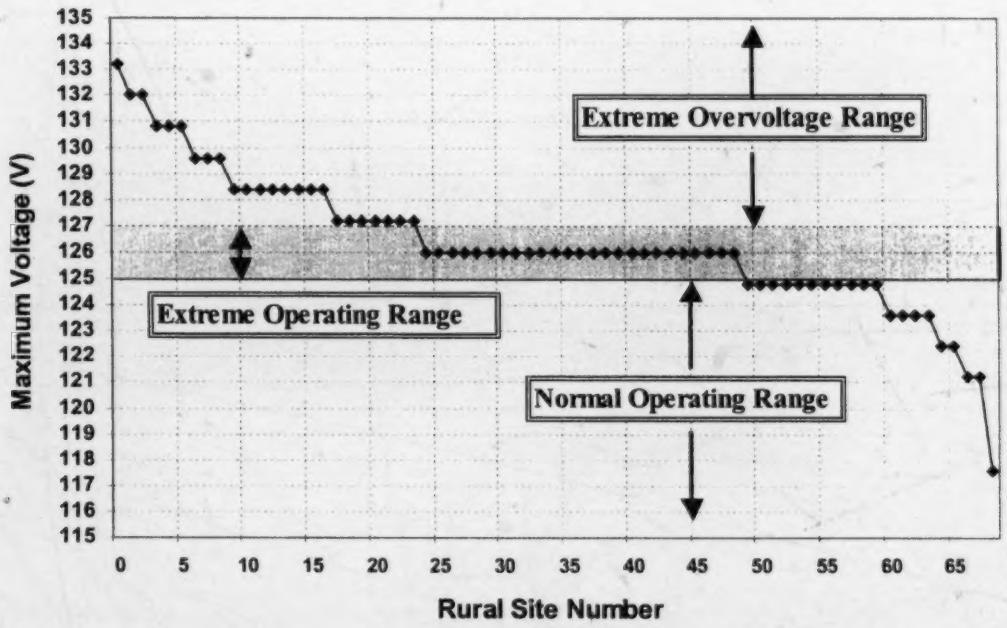


Figure 2-12 The Maximum Voltage Level at Each Rural Site (Service Entrance)

It is observed from Figure 2-12 that Site 0128 had the lowest maximum voltage level of 117.6V, which was below the nominal voltage 120V. Was the voltage at Site 0128 extremely low? What was its minimum voltage level? The minimum voltage level at Site 0128 was 109.2V, and the average voltage level was 114.52V.

There are 49 sites had the maximum voltage level above 125V within the extreme high operating voltage range of 126V which was the most common maximum voltage level. The highest maximum voltage is 133.2V at Site 0282. The average voltage of Site 0282 was 124.29V.

Table 2-4 shows the correspondence between the CEA rural Site ID and its corresponding site number labeled in Figure 2-12.

Table 2-4. Site Name & Corresponding Number for the Maximum Voltage Plot

CEA Site ID	Number	CEA Site ID	Number	CEA Site ID	Number
SITE0282	1	SITE0166	24	SITE0073	47
SITE1086	2	SITE1083	25	SITE0056	48
SITE0543	3	SITE0616	26	SITE0052	49
SITE1080	4	SITE0600	27	SITE0479	50
SITE0169	5	SITE0523	28	SITE0454	51
SITE0167	6	SITE0478	29	SITE0398	52
SITE0278	7	SITE0446	30	SITE0298	53
SITE0091	8	SITE0444	31	SITE0288	54
SITE0037	9	SITE0438	32	SITE0271	55
SITE1042	10	SITE0437	33	SITE0252	56
SITE0535	11	SITE0432	34	SITE0235	57
SITE0443	12	SITE0428	35	SITE0148	58
SITE0425	13	SITE0424	36	SITE0124	59
SITE0324	14	SITE0399	37	SITE0015	60
SITE0103	15	SITE0329	38	SITE1092	61
SITE0082	16	SITE0285	39	SITE0411	62
SITE0034	17	SITE0281	40	SITE0234	63
SITE1018	18	SITE0272	41	SITE0213	64

Table 2-4. (Continued)

CEA Site ID	Number	CEA Site ID	Number	CEA Site ID	Number
SITE0605	19	SITE0218	42	SITE0539	65
SITE0541	20	SITE0206	43	SITE0064	66
SITE0515	21	SITE0175	44	SITE0433	67
SITE0488	22	SITE0168	45	SITE0423	68
SITE0459	23	SITE0112	46	SITE0128	69

Figure 2-13 shows the average voltage level at each rural site. The average voltage is calculated by summing the product of each voltage and the percentage of time this voltage appeared during the total monitored period. The horizontal axis of Figure 2-13 is the number of rural sites, which is actually the ascending order of the average voltage levels.

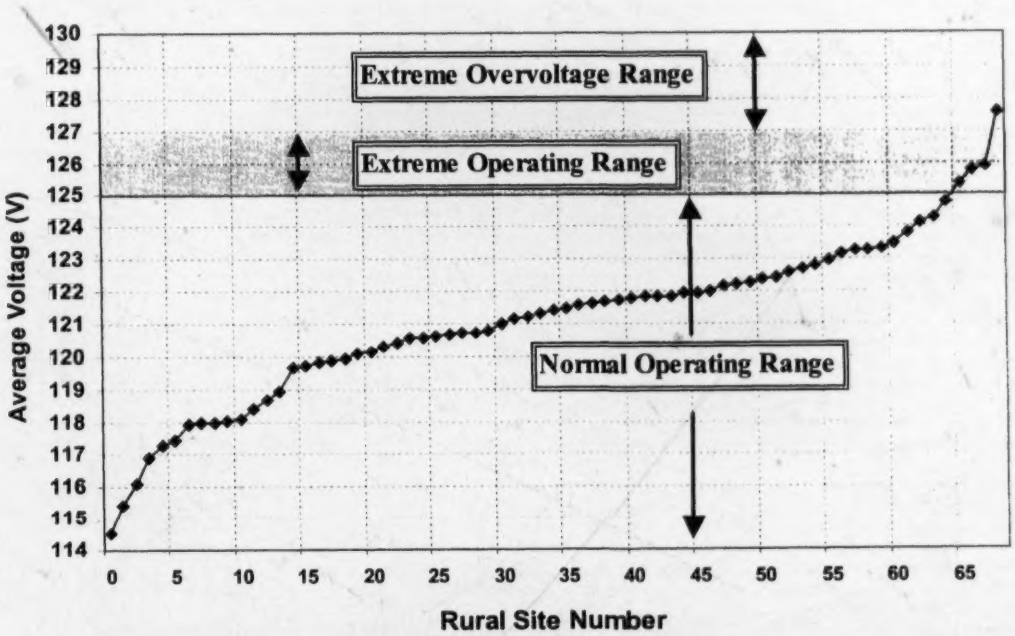


Figure 2-13 Average Voltage Level at Each Rural Site (Service Entrance)

With reference to Figure 2-13, most sites, 65 out of 69, had the average voltage level within the normal operating voltage range, from 114V to 125V. However, the other four sites, Site 0425, Site 0398, Site 1086 and Site 1042, had an average voltage above 125V in the extreme high range. The individual site voltage histogram of Site 1086 is shown in the above Figure 2-6. It can be seen that the voltage level of this site was extremely high.

Table 2-5 shows the correspondence between the CEA rural Site ID and its corresponding site number labeled in Figure 2-13.

Table 2-5. Site ID & Corresponding Number for the Average Voltage Plot

CEA Site ID	Number	CEA Site ID	Number	CEA Site ID	Number
SITE0235	1	SITE0543	24	SITE0428	47
SITE0541	2	SITE0064	25	SITE0423	48
SITE1080	3	SITE0128	26	SITE0479	49
SITE0112	4	SITE0488	27	SITE0015	50
SITE0073	5	SITE0175	28	SITE0285	51
SITE0433	6	SITE0539	29	SITE0523	52
SITE0444	7	SITE0324	30	SITE0103	53
SITE0213	8	SITE0437	31	SITE0056	54
SITE0616	9	SITE0169	32	SITE1083	55
SITE0034	10	SITE0037	33	SITE1092	56
SITE0052	11	SITE0298	34	SITE0411	57
SITE0443	12	SITE0272	35	SITE0166	58
SITE0252	13	SITE0515	36	SITE0605	59
SITE0282	14	SITE0278	37	SITE0424	60
SITE0432	15	SITE0399	38	SITE0478	61
SITE0454	16	SITE0446	39	SITE0459	62

Table 2-5. (Continued)

CEA Site ID	Number	CEA Site ID	Number	CEA Site ID	Number
SITE0438	17	SITE0206	40	SITE0167	63
SITE0329	18	SITE0535	41	SITE0281	64
SITE0600	19	SITE1018	42	SITE0288	65
SITE0148	20	SITE0124	43	SITE0425	66
SITE0168	21	SITE0091	44	SITE0398	67
SITE0234	22	SITE0218	45	SITE1086	68
SITE0082	23	SITE0271	46	SITE1042	69

In summary, the long-term steady-state rural voltage profiles are significantly different from site to site. The average voltage levels in rural areas were mostly within the normal operating voltage range. A significant number of sites had maximum voltage levels above 125V in the extreme operating condition boundaries.

2.3 Feeder Length VS. the Voltage Level

The long rural lines might either boost the utilization voltage with the effect of the distributed capacitance or lower the utilization voltage due to the extreme length of the utility feeders.

To reveal the effect of feeder cable length on the site voltage level, Figures 2-14 to 2-16 plot the minimum, maximum and average voltage levels versus their corresponding feeder physical length at rural sites.

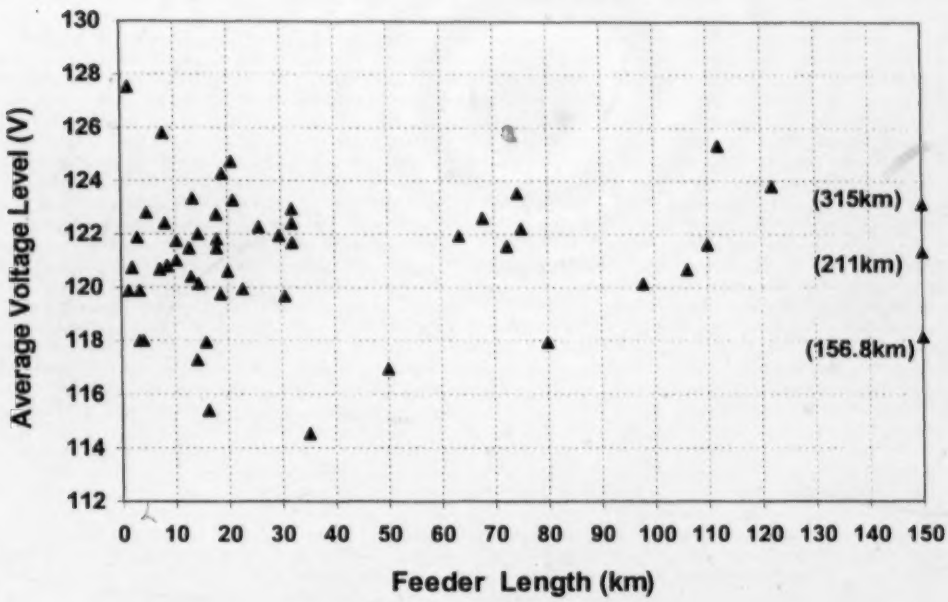


Figure 2-14 Average Voltage Versus Corresponding Feeder Length

It appears from Figure 2-14 the length of the rural lines was not clearly dependent upon the distance from the rural site to the substation. With the increase of the feeder length, there is no apparent rising of the average site voltage.

Figure 2-15 and 2-16 present the minimum and maximum of site voltage level vs. the feeder length separately. The minimum and maximum voltage level were not in proportion with the feeder physical length. There is no evident proof to show that the feeder physical length has an effect on site minimum or maximum voltage.

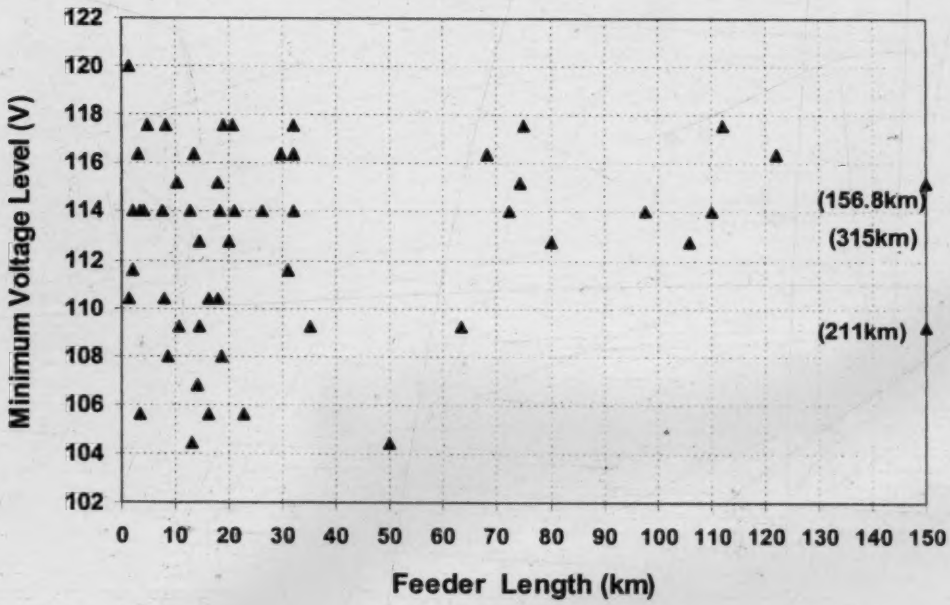


Figure 2-15 Minimum Voltage Versus Corresponding Feeder Length

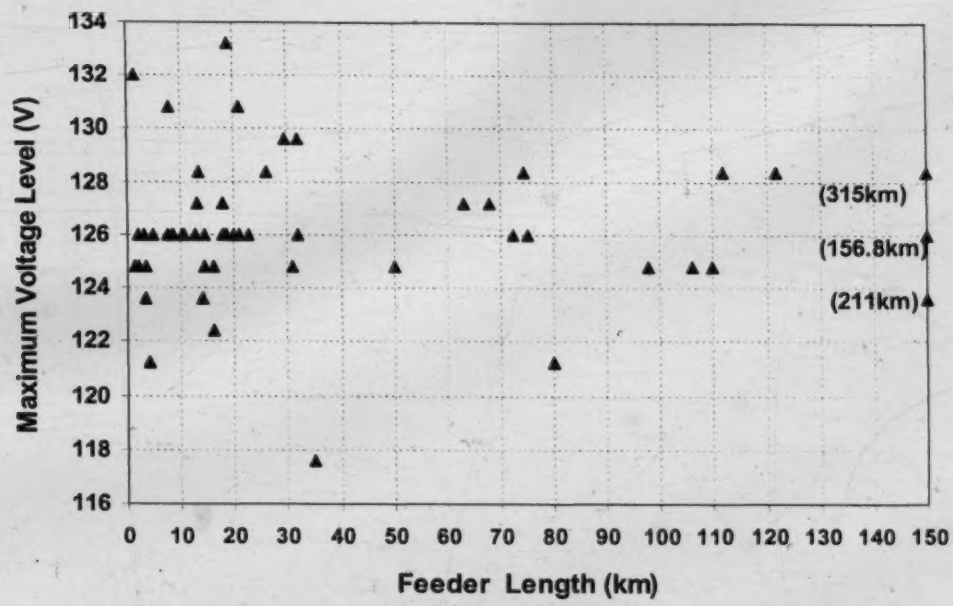


Figure 2-16 Maximum Voltage Versus Corresponding Feeder Length

2.4 Voltage Waveform Distortion

The voltage waveform distortion caused by the rural loads is a concern for both the utilities and their rural customers. The percentage of steady-state voltage total harmonic distortion (% THD) of the 69 rural sites were recorded and analyzed. No other harmonic indices were available in the survey.

Figure 2-17 shows the percentage of total harmonic distortion (% THD) of the voltage at each rural site service entrance monitored.

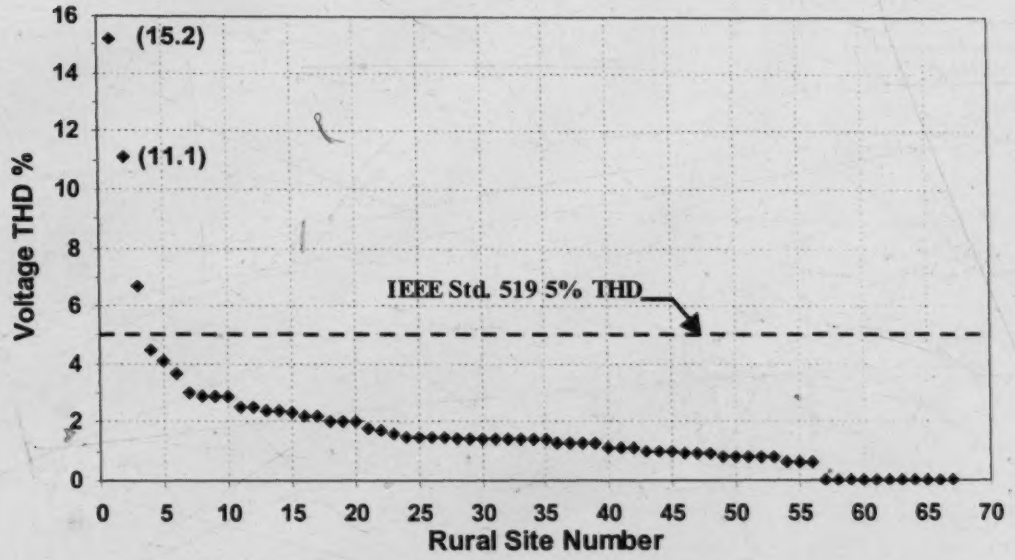


Figure 2-17 Voltage THD of at Each Rural Site Service Entrance

Result show that the average THD was 1.79%. Most of the rural sites, 65 out of 69, had THD lower than 5%. Compared to the often-adopted standard of 5% in the IEEE Std. 519, the majority of utility supplies conformed to IEEE 519 Standard.

2.5 Conclusions

In this chapter, the long term steady-state voltage profile of each rural site has been invegistated and compared with the CAN3-C235-83 Standard accordingly, including the voltage levels at the service entrance and those at the utilization point. Shows where utilities can improve service by using transformer taps or feeder regulator to shift the voltage profile.

The minimal, maximal and average voltage of each site has been ranked and tabulated. It has been revealed that the rural voltage level dwelled in the "extremly overvoltage range" for a considerable period of time.

No apparent evidence shows that the feeder length affected rural site long term steady-state voltage levels directly.

Result show that the average THD at rural was 1.79%. The majority of utility supplies to rural customers conformed to IEEE 519 Standard.

Chapter 3 Statistical Characteristics of Rural Voltage Disturbances

This chapter will statistically analyze the CEA rural power quality database and present its findings. The patterns of occurrence (e.g., time of day, day of week, etc.) of voltage sags, swells and surges that occurred at these rural sites will be presented and discussed. The distribution of magnitude and duration of these voltage disturbances are presented to build the empirical knowledge base of the rural electric environment.

3.1 CEA Rural Voltage Disturbances

As introduced in the Chapter 1, there are mainly five types of voltage disturbances captured in the CEA survey: voltage sags, swells, surges, waveshape faults and outages. The power-line threshold levels for disturbances can be found in Table 1-3. The percentage of the various types of rural voltage disturbances is shown in Figure 3-1.

Voltage surges, swells and sags add up to over 99% of all the voltage disturbances the rural customer experienced. How to mitigate these types of disturbances would, therefore, be of primary importance to rural customers.

In order to mitigate these power supply disturbances a statistical knowledge base of the frequency, magnitude and duration of these disturbances as well as the site voltage profiles as a function of the time in a day is required.

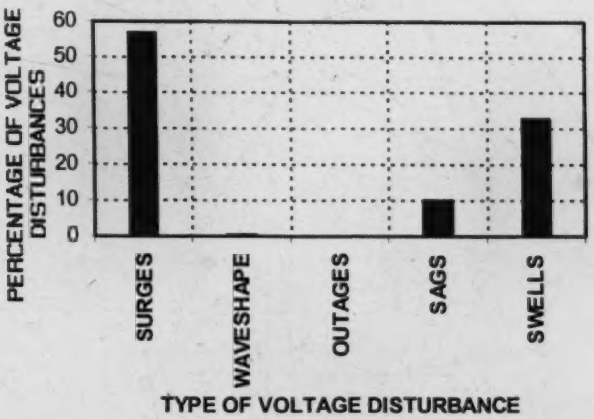


Figure 3-1 Frequency of Different Disturbances at Rural Sites

This chapter will statistically analyze the voltage profiles of the rural sites and reveal some of the statistical characteristics of rural power supply disturbances (i.e., voltage sags, voltage swells and surges) experienced by rural customers. The results will describe the rural electric supply environment and provide a guide for designing rural electric equipment and choosing mitigation techniques.

3.2 Voltage sags

Voltage sags were captured at 58 out of 69 sites. There are 47 sites that had no more than 20 sags per month. Only 6 rural sites monitored had over 100 sags in a one-month period. However, Site .0454 had 1335 sags recorded. The large number of voltage sags captured

at Site 0454 was due to neutral-grounding problems. These statistics were excluded from the rural group statistics and were considered an extreme outliner. The number of voltage sags per phase happened at each rural site is sorted and shown in Figure 3-2. The table which shows the corresponding rural site ID to the ordered number is in Appendix B.

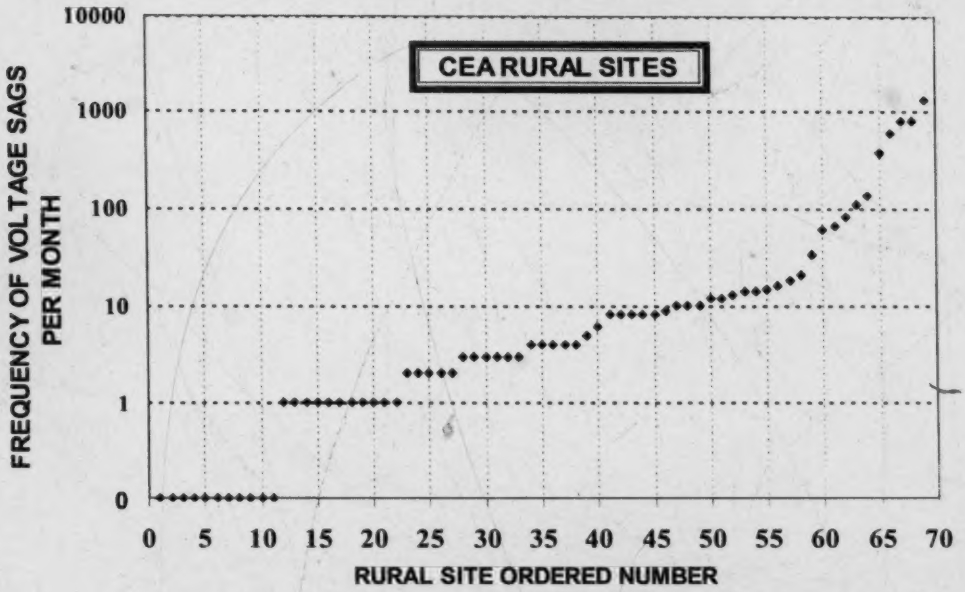


Figure 3-2 Frequency of Voltage Sags Per Month at Each Rural Site

The occurrence frequency of voltage sags versus the time in a day is shown in Figure 3-3. If the occurrence of voltage sags is assumed to follow a uniform distribution then the frequency histogram would be a horizontal line as illustrated in Figure 3-3.

It appears from Figure 3-3 that voltage sags tend to follow the daily loading pattern of the utility at these rural sites, i.e., the utilities response to changing demands appears to cause more voltage sags at certain time of the day. As shown in Figure 3-4, the utility daily load

curve usually have two peaks. The voltage sags occur more frequently when the loads are heavy at 10:00am and 18:00 pm when the load curve peaks. The frequency of voltage sags is low when the rural loads are light, from midnight to the early morning.

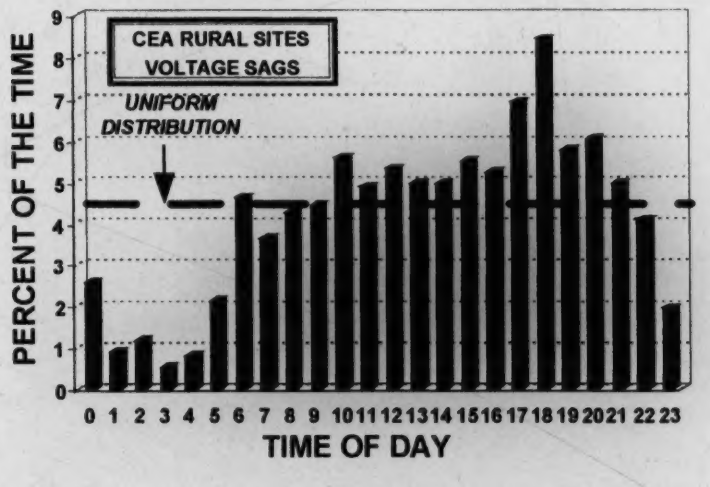

CEA RURAL SITES
VOLTAGE SAGS
UNIFORM
DISTRIBUTION
PERCENT OF THE TIME
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
TIME OF DAY

Figure 3-3 Voltage Sags as a Function of the Time in a Day

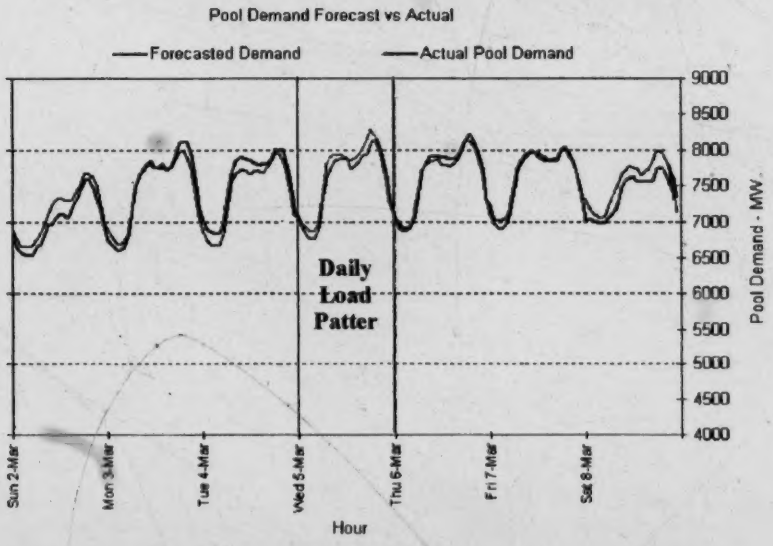


Figure 3-4 a Alberta Power Pool Weekly Demand Report

Voltage sags as a function of the day in a week is shown in Figure 3.5.

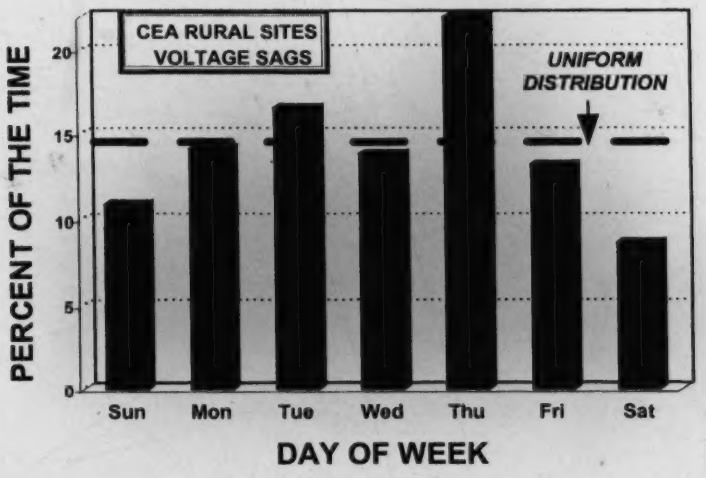


Figure 3-5 Voltage Sags as a Function of the Day in a Week

Voltage sags tend to occur uniformly in a week. They occur more frequently during weekdays than weekends. It remains unexplained why there were so many sags on Thursday. The origins of voltage sags can be specifically identified by a detailed on-site power quality audit [5].

Figure 3-6, 3-12 & 3-18 show the magnitude of voltage sags, swells & surges as the function of their duration separately. These figures were drawn in [11]. They are included here to keep the continuality of the description.

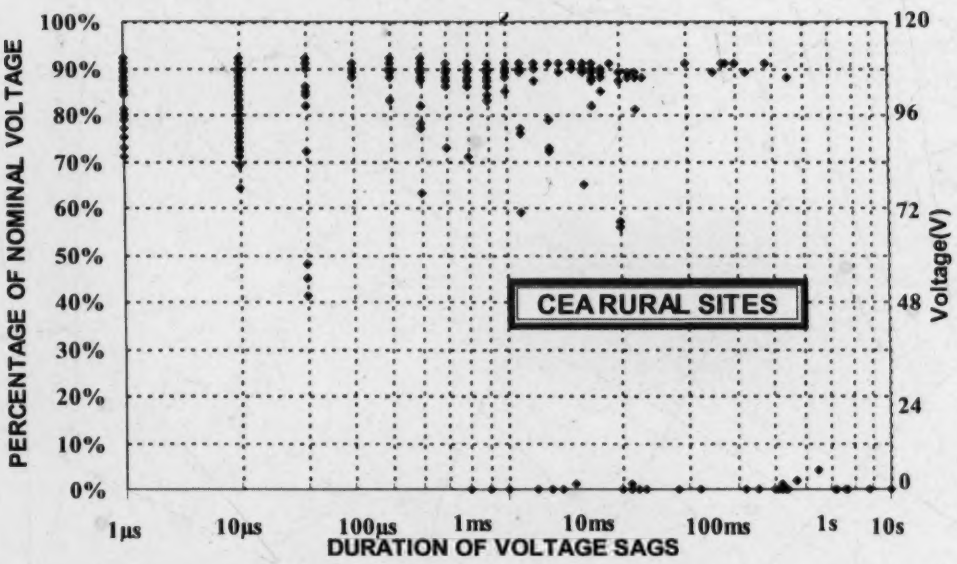


Figure 3-6 Magnitude of Voltage Sags as a Function of Their Duration

Distribution of voltage sags' magnitudes and durations are shown in the Figure 3-7 and Figure 3-8 separately.

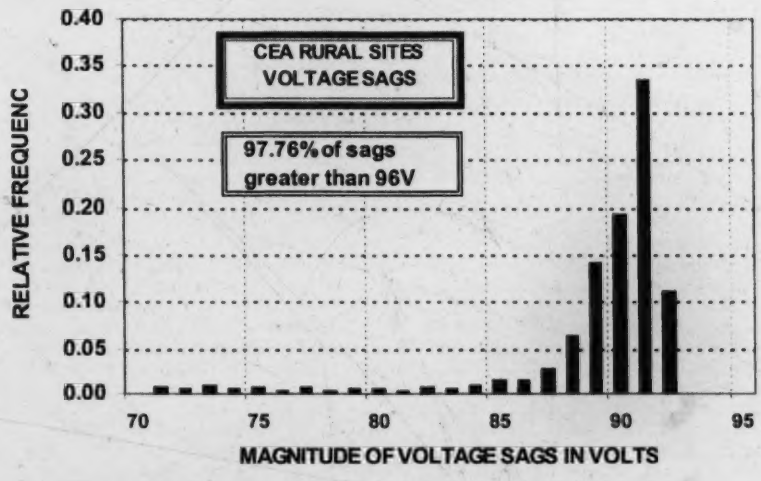


Figure 3-7 Distribution of the Magnitude of Voltage Sags

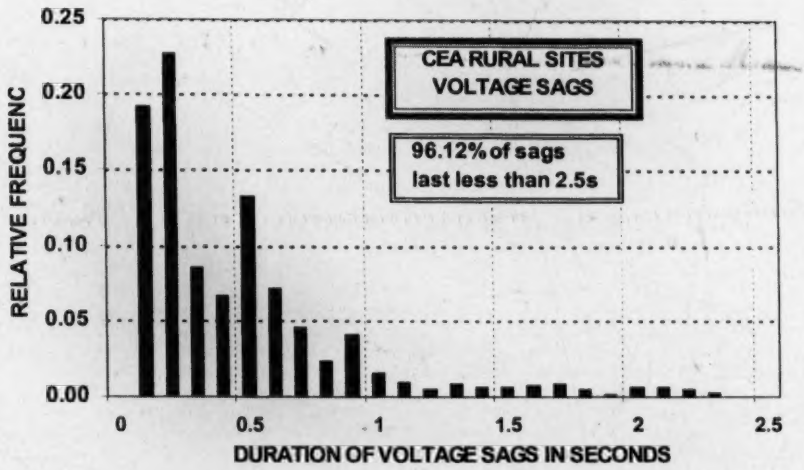


Figure 3-8 Distribution of the Duration of Voltage Sags

Voltage sags statistical characteristics are summarized in the following Table 3-1, in which the voltage magnitude is as percentage of nominal voltage. Most voltage sags have the magnitude between 87% and 92% of nominal voltage and most of them last for a duration less than 1 second.

Table 3-1. Voltage Sags Statistical Characteristics

MAGNITUDE	VALUE		DURATION	VALUE
Average Magnitude	85.73%	102.88V	Average Duration	0.594s
Mode	91%	109.20V	Mode	0.2s
Standard Deviation	17.32%	20.78V	Standard Deviation	0.94s
Minimal Magnitude	0	0.00V	Minimal Duration	0.1s
Maximal Magnitude	92%	110.40V	Maximal Duration	10s

3.3 Voltage Swells

An average of 222.5 voltage swells per site was captured in the CEA survey. At seven sites Number voltage swells were captured. The maximum number of voltage swells captured a site was 1281. The frequency of voltage swells per month for each rural site is shown in Figure 3-9.

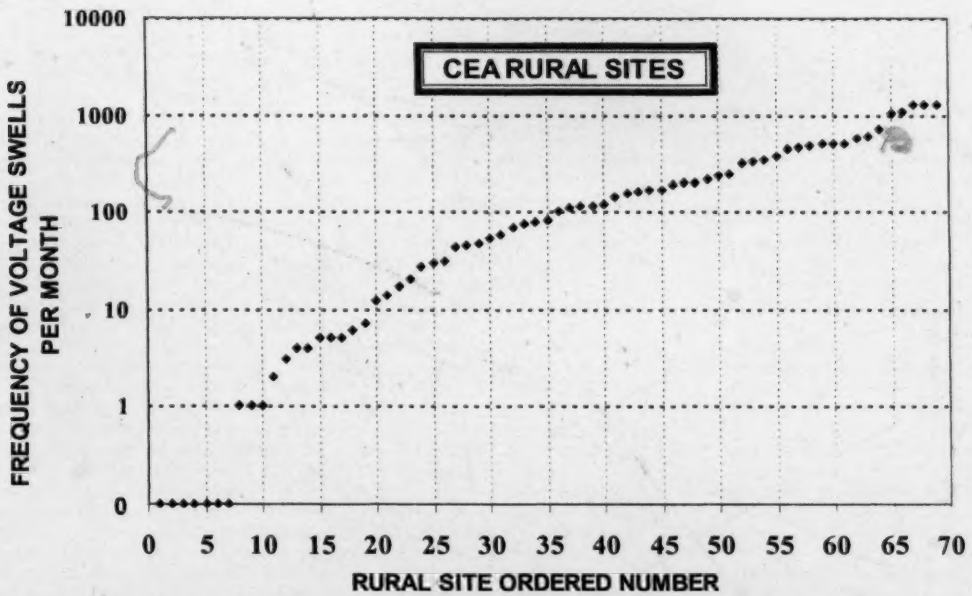


Figure 3-9 Frequency of Voltage Swells Per Month at Each Rural Site

Voltage swells as a function of the time in a day are shown in Figure 3-10.

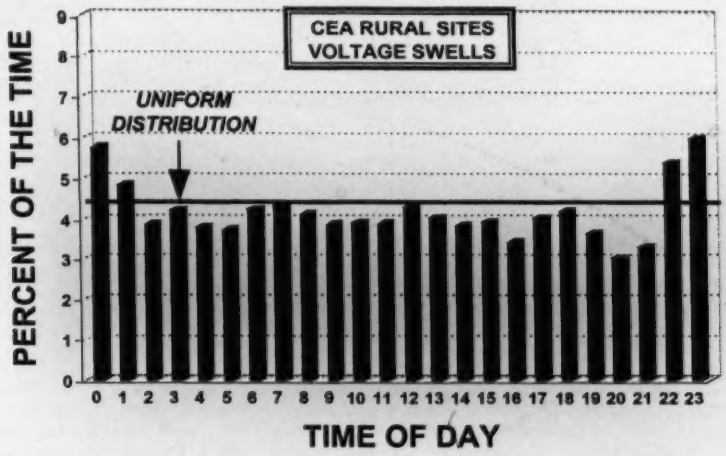

CEA RURAL SITES
VOLTAGE SWELLS
UNIFORM
DISTRIBUTION
PERCENT OF THE TIME
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
TIME OF DAY

Figure 3-10 Voltage Swells as a Function of the Time in a Day

It can be seen that the ocurrence parttern of voltage swells monitored at rural sites related to the utility daily load parttern too. The daily distribution curve of voltage swells is kind of converse to that of voltage sags. When the loads were heavry, the occurrence frequency of voltage swells was low, and the voltage swell hourly frequency curve reached the lowest point while the curve of voltag sags had a peak. When the loads were light, the occurrence of voltage swells was more frequently while the occurrence frequency of voltage sags was low.

Voltage swells as a function of the day in a week monitored at the rural sites is shown in Figure 3-11. It appears from Figure 3-11 that voltage swells occurred uniformly during the day in a week.

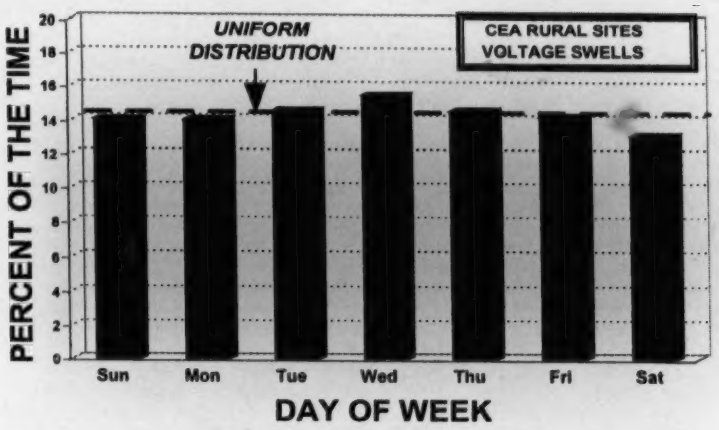


Figure 3-11 Voltage Swells as a Function of the Day in a Week

A Chi-square test has been carried out to the voltage swell data to test the hypothesis that voltage swells were distributed uniformly in a week and therefore that H_0: $p_1 = p_2 = p_3 = p_4 = p_5 = p_6 = p_7 = 1/7 = 14.28\%$. The total number of voltage swells is 9302 and the expected daily count is 9302/7 = 1328.857. Here, H_0 denotes the null hypothesis, and p_i represents the possibility of swells occurring on a specific day in a week, i = 1, 2, 3, 4, 5, 6, 7 (starting from Sunday to Saturday). The observed and expected daily frequencies are presented in Table 3-2.

Table 3-2. Observed and Expected Daily Swells Counts

	1	2	3	4	5	6	7
Observed Daily Frequency	1308	1305	1352	1440	1353	1322	1222
Expected Daily Frequency	1328.9	1328.9	1328.9	1328.9	1328.9	1328.9	1328.9

Since the only restriction on the observations is that $\sum_{i=1}^{7} p_i = 1$, the Chi-square test will possess (7-1) = 6 degrees of freedom. Therefore, if we chose $\alpha = 0.05$ (α denotes the possibility of Type I error), the null hypothesis will be rejected when $X^2 > 12.5916$ according to the table of Critical Values of Chi-square.

Substituting into the formula for X^2, we obtain $X^2 = \sum_{i=1}^{7} \frac{[p_i - E(p_i)]^2}{E(p_i)} = 19.52$. Since X^2 is greater than the tabulated critical value, the null hypothesis is rejected, and we conclude that the data do not present sufficient evidence to indicate that the voltage swells have a uniformly distribution in each day of a week.

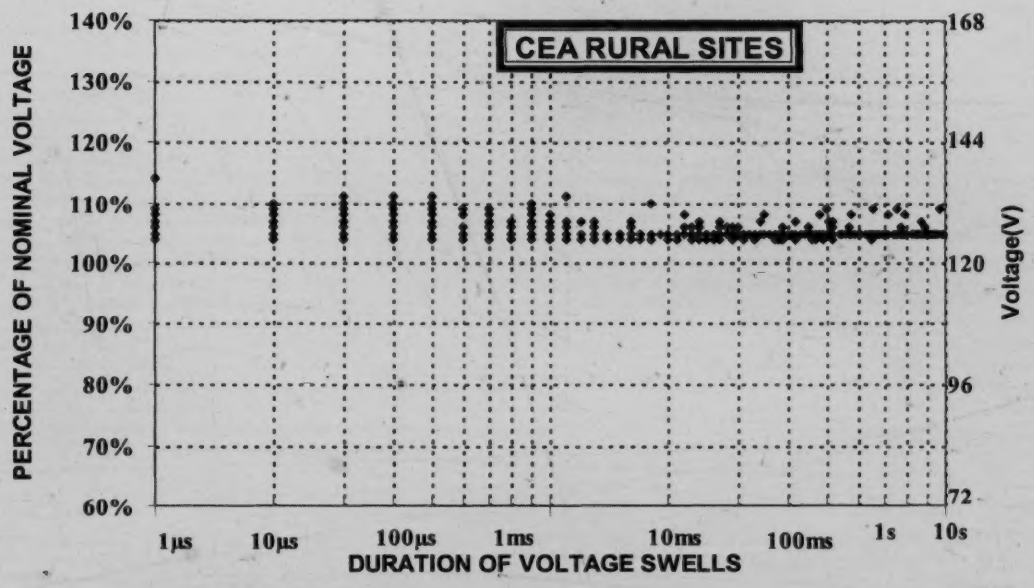


Figure 3-12 Magnitude of Voltage Swells vs. Their Duration

The magnitude and duration of voltage swells is plotted in Figure 3-12. Distribution of voltage sags' magnitudes and durations are shown in the Figure 3-13 and Figure 3-14 separately.

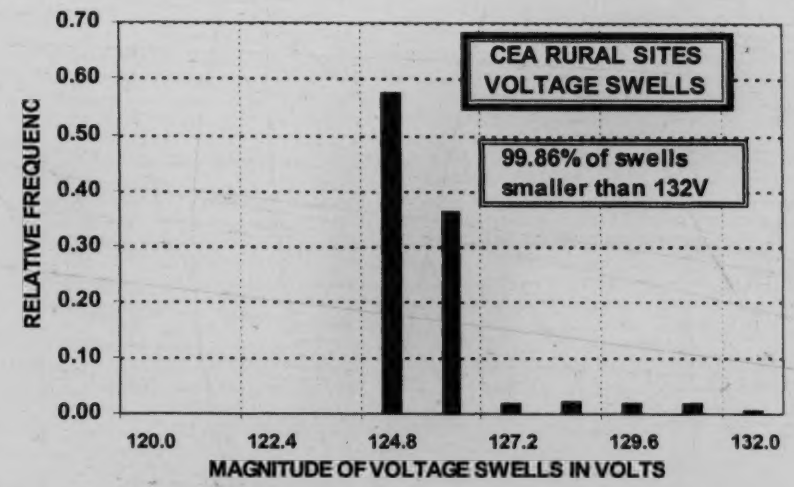


Figure 3-13 Distribution of the Magnitude of Voltage Swells

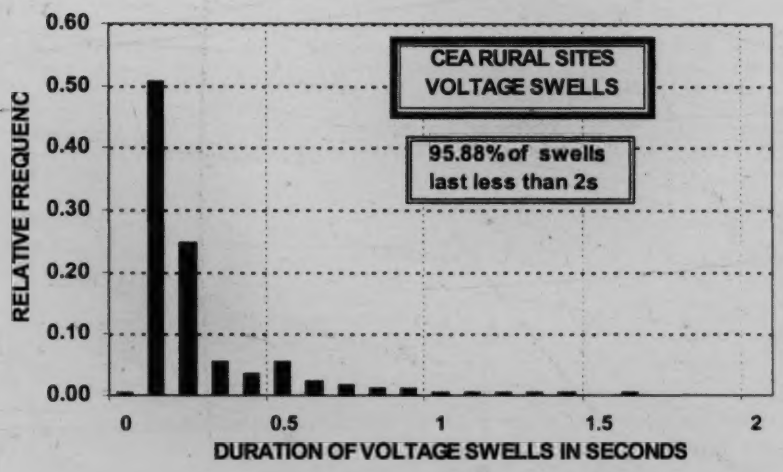


Figure 3-14 Distribution of the Duration of Voltage Swells

Voltage swells statistical characteristics in shown Table 3-3. Most voltage swells had the mangitude 104% or 105% of the nominal voltage and the duration ranges from 0.1s to 1s.

Table 3-3. Voltage Swells Statistical Characteristics

MAGNITUDE	VALUE		DURATION	VALUE
Average Magnitude	104.62%	125.54V	Average Duration	0.431s
Mode	104%	124.80V	Mode	0.1s
Standard Deviation	1.10%	1.32V	Standard Deviation	1.09s
Minimal Magnitude	104%	124.80V	Minimal Duration	0
Maximal Magnitude	130%	156.00V	Maximal Duration	9.9s

3.4 Voltage Surges

Voltage surges occurred at 67 out of the 69 rural sites. The average frequency of occurrence of voltage surges was 385.5 per site per month. Voltage surges were the most common type of disturbance at rural sites. The actual frequency of voltage surges per month for each rural site is shown in Figure 3-15.

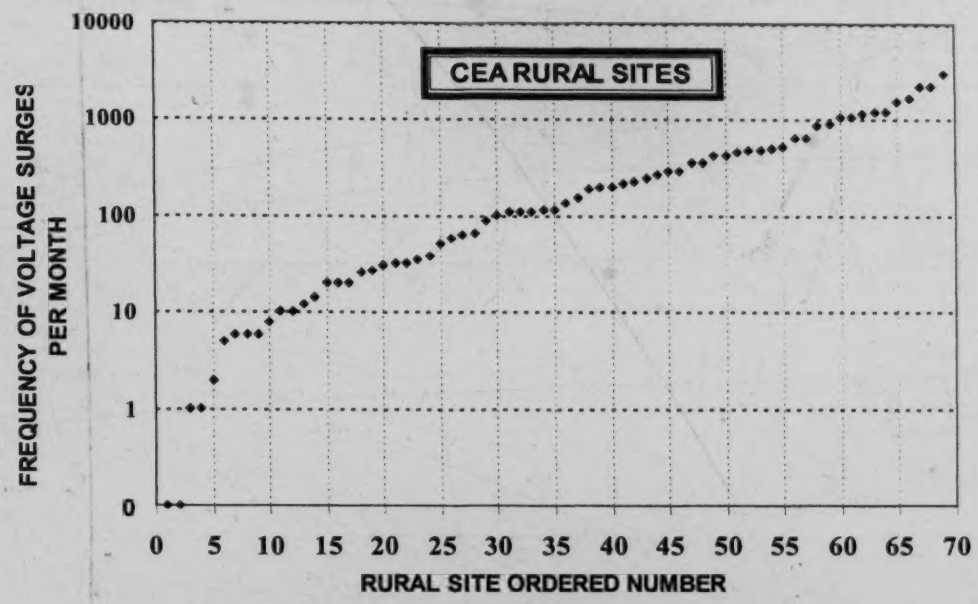


Figure 3-15 Frequency of Voltage Surges Per Month for Each Rural Site

The frequency of occurrence of voltage surges versus the time of day in which it occurred is shown in Figure 3-16.

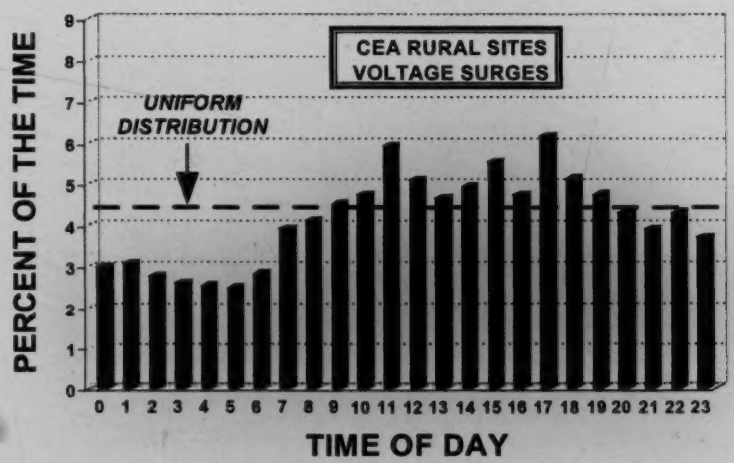

CEA RURAL SITES
VOLTAGE SURGES
UNIFORM DISTRIBUTION
PERCENT OF THE TIME
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
TIME OF DAY

Figure 3-16 Voltage Surges as a Function of the Time in a Day

Voltage surges are usually caused by load switching activities (e.g., switching load on and off). These activities tended to occur more frequently between 9:00am. and 19:00pm, during this period the voltage surges' occurrence frequency was greater than that supposing voltage surges follow the uniform distribution.

A frequency histogram of the voltage surges as a function of the day in a week in which they occurred is shown in Figure 3-17. The occurrence of voltage surges during the week appears to follow a uniform distribution. A Chi-square test was performed for the daily occurrence pattern of voltage surges similarly with the one for voltage swells described in detail before. X^2 (24.76, 6) is greater than the critical Chi-square value (12.59, 6) and the hypothesis that voltage surges are distributed uniformly during each day in a week has been rejected.

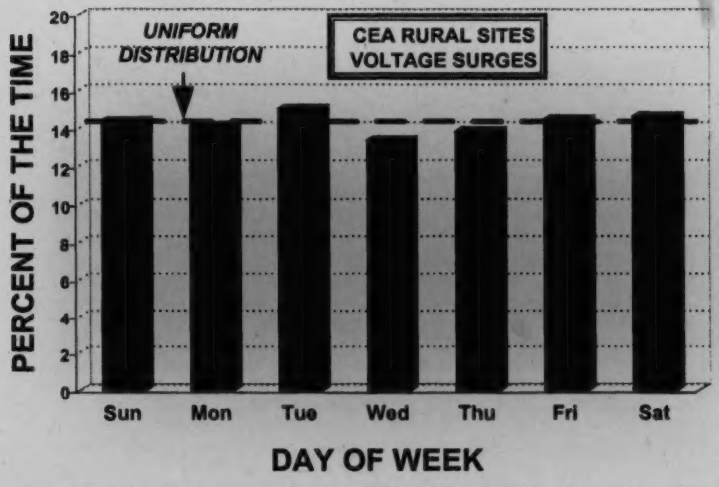


Figure 3-17 Voltage Surges as a Function of the Day in a Week

Voltage surges were divided into positive and negative surges instead of taking their absolute value. Because the direction of the voltage surges has a significant impact on electronic equipment, like switching rectifiers on and off, breaking down electric equipment insulation, etc. [1].

The magnitude and duration of voltage surges, both positive and negative, is shown in Figure 3-18. The distribution of magnitude and duration of negative and positive surges is shown in Figure 3-19 to 3-22 separately.

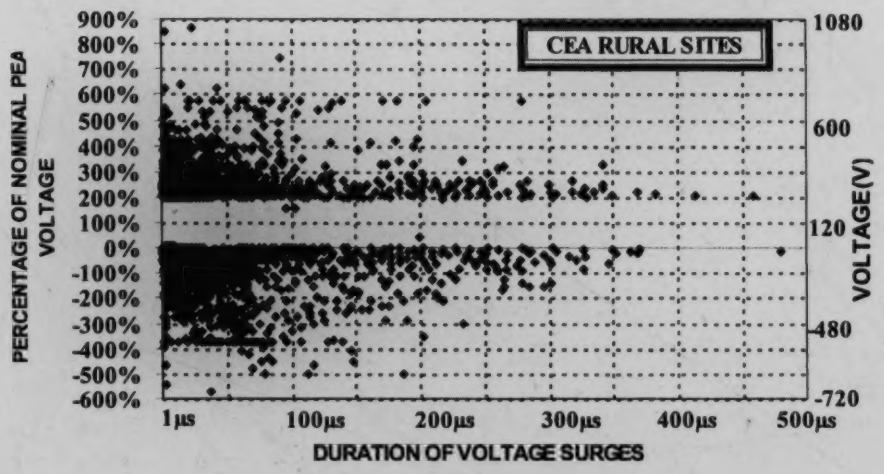


Figure 3-18 Voltage Surge Magnitude vs. Duration

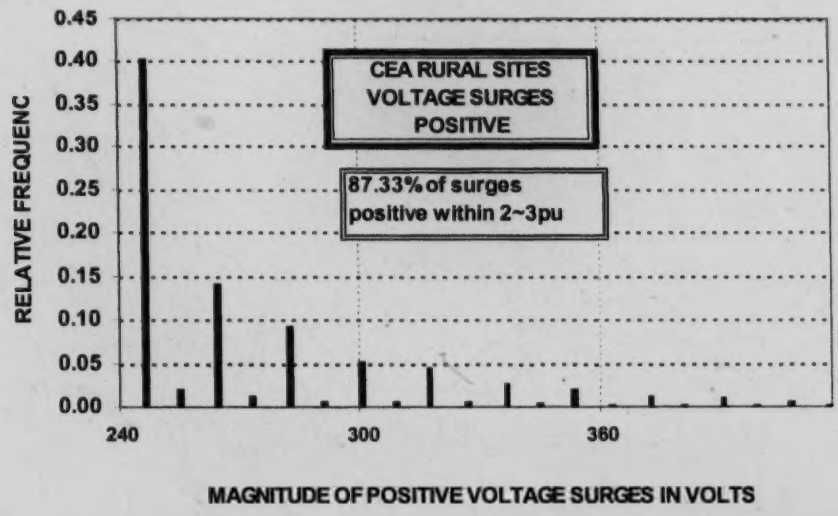


Figure 3-19 Distribution of the Magnitude of Positive Voltage Surges

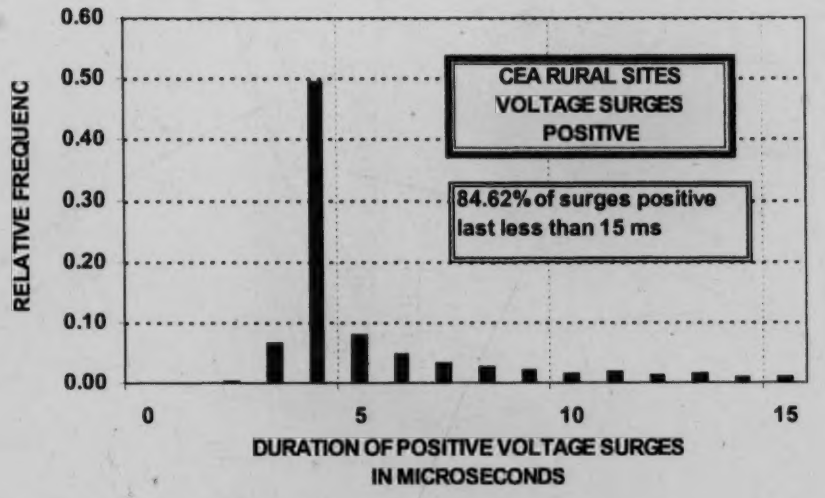


Figure 3-20 Distribution of the Duration of Positive Voltage Surges

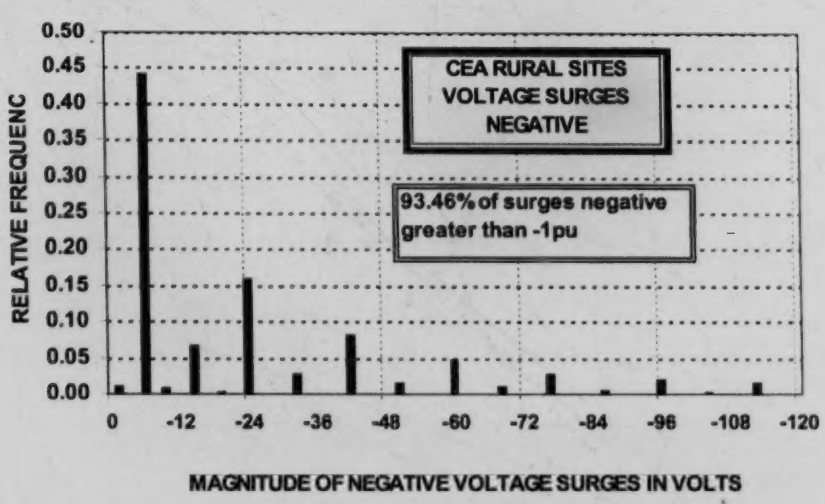


Figure 3-21 Distribution of the Magnitude of Negative Voltage Surges

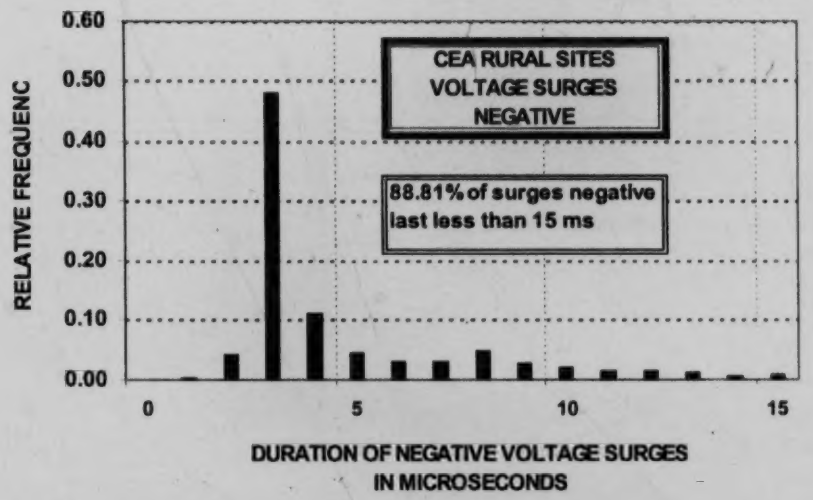


Figure 3-22 Distribution of the Duration of Negative Voltage Surges

The statistical characteristics of magnitude and duration of positive and negative voltage surges are presented in Table 3-4 and 3-5. For the positive voltage surges, 87.3% of them

fall into the mangitude range from 200% to 300% of the nominal voltage and 86.1% of the positive voltage surges lasted from 1μs to 15μs. For negative voltage surges, 93.4% of the total ranges from -5% to -100% of the nominal voltage in mangitude and 88.8% of the negative voltage surges lasted from 1us to 15μs in duration.

Table 3-4. Positive Voltage Surges Statistical Characteristics

MAGNITUDE	VALUE		DURATION	VALUE
Average Magnitude	214.27%	257.12V	Average Duration	0.431s
Mode	205%	246.00V	Mode	0.1s
Standard Deviation	79.91%	95.89V	Standard Deviation	1.09s
Minimal Magnitude	3%	3.60V	Minimal Duration	0
Maximal Magnitude	1043%	1251.60V	Maximal Duration	9.9s

Table 3-5. Negative Voltage Surges Statistical Characteristics

MAGNITUDE	VALUE		DURATION	VALUE
Average Magnitude	-31.74%	-38.09V	Average Duration	0.431s
Mode	-5%	-6.00V	Mode	0.1s
Standard Deviation	54.89%	65.87V	Standard Deviation	1.09s
Minimal Magnitude	-648%	-777.60V	Minimal Duration	0
Maximal Magnitude	-1%	-1.20V	Maximal Duration	9.9s

The differences in many of the statistical characteristics between the positive and negative voltage surges are small. However, the maximum magnitude of the positive voltage surges significantly exceeds the negative voltage surges.

3.5 Outages

Outages are defined as voltage sags of zero volts that last more than 10 seconds. Outages directly disrupted the power supply of rural customers, a costly issuer for rural society. Figure 3-22 shows the frequency of outages per month for each rural site.

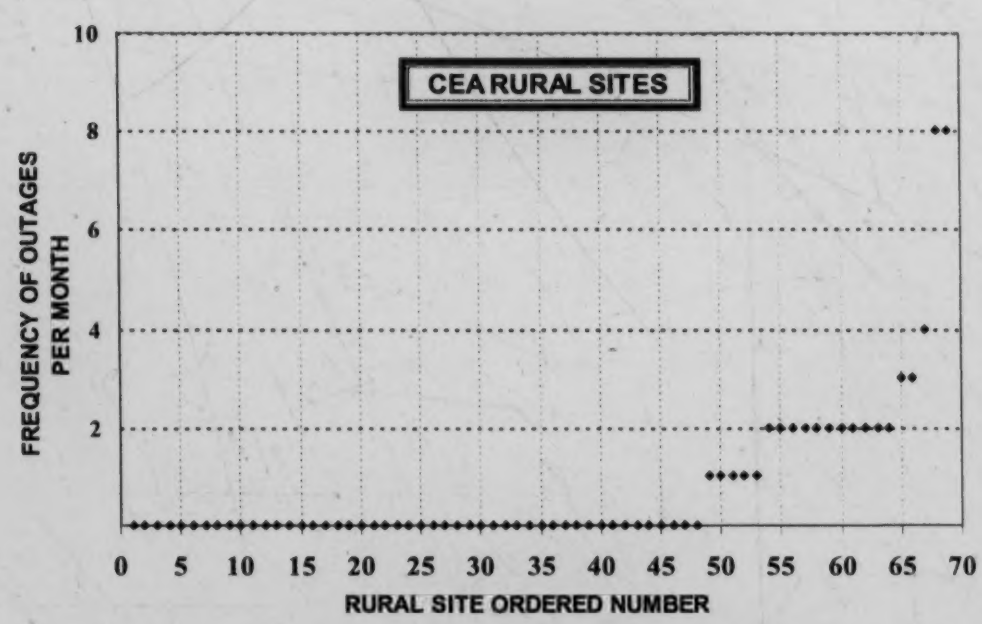


Figure 3-22 Frequency of Outages at Each Rural Site

21 out of 69 rural sites experienced power shutoff within one month in the CEA survey. Among them, 5 sites had an outage once per month, 11 sites had twice, 2 sites had 3 each, and 1 site had 4 outages in a month. There are 2 sites, Site 0052 and Site 0091, which experienced 8 outages each in a month.

Effort has been made to find out the reason why these two sites had such frequent outages. For the Site 0052, the utility transferred customer to new phase one day, and experienced a wind and rainstorm the other day. The transfer and the atrocious weather caused the frequent outages. However, for the Site 0091, there was no detailed record and it remains unexplained why it had so many outages.

The magnitude and duration of outages are statistically calculated in Table 3-6.

Table 3-6. Voltage outages statistical characteristics

MAGNITUDE	VALUE		DURATION	VALUE
Average Magnitude	0%	0V	Average Duration	20.7s
Mode	0%	0V	Mode	16.1s
Standard Deviation	0%	0V	Standard Deviation	23.0s
Minimal Magnitude	0%	0V	Minimal Duration	10.9s
Maximal Magnitude	0%	0V	Maximal Duration	126.0s

It should be noted that because the outages did not show up in the power quality envelope because they all lasted more than 10 minutes.

3.6 Waveshape faults

The instantaneous voltage of a fraction of an ac cycle was recorded and compared with the same portion of the previous cycle. If the comparison shows that the difference exceeds a user supplied wave tolerance and lasts longer than a user supplied minimum duration, like ±50V and 0.1 cycle of 60 Hz in the CEA survey. According to IEEE 519, shorter duration waveshape faults (1ms~8.3ms) here are transients and the remaining waveshape faults (8.3ms~80ms) belong to the group of either sags or swells.

The frequency of voltage waveshape faults per month for each rural site is shown in Figure 3.23. 30 out of 69 sites have no waveshape faults recorded at all in the monitored month. Only 3 sites had experienced more then 20 waveshape faults per month.

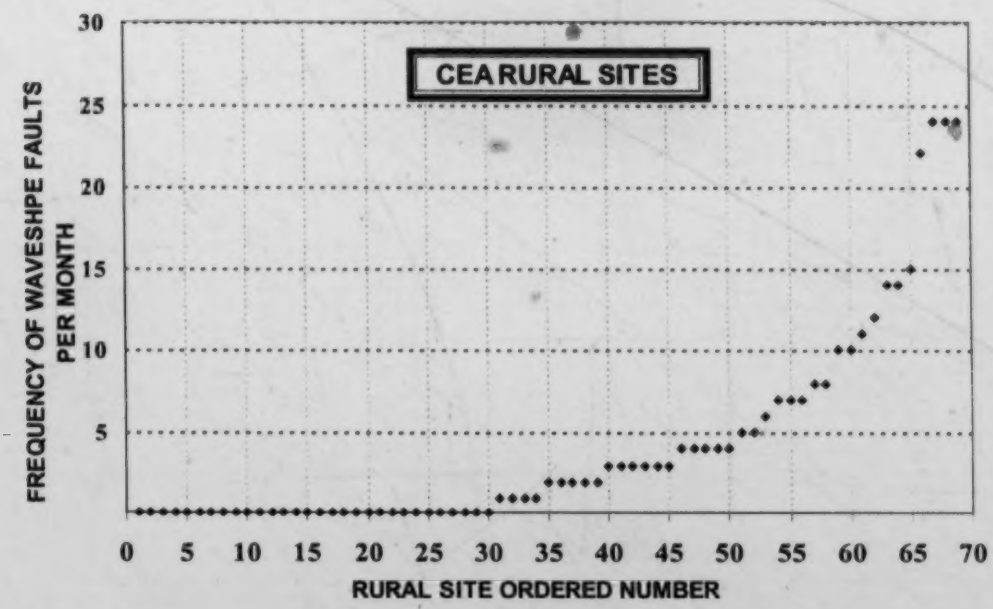


Figure 3-23 Frequency of Waveshape Faults at Each Rural Site

The magnitude and duration of waveshape faults are statistically calculated in Table 3-7.

Table 3-7. Voltage waveshape faults statistical characteristics

MAGNITUDE	VALUE		DURATION	VALUE
Average Magnitude	41.9%	50.28V	Average Duration	28.4ms
Mode	60%	72.00V	Mode	7.8ms
Standard Deviation	17.9%	21.48V	Standard Deviation	27.2ms
Minimal Magnitude	-3%	-3.60V	Minimal Duration	1.47ms
Maximal Magnitude	75%	90.00V	Maximal Duration	82.4ms

3.7 Conclusions

The statistical characteristics of rural voltage disturbances have been presented in this chapter. Voltage surges, voltage swells and votlage sags were the majority of the diturbances rural electric experienced. Their occurrence parterns as a function of the time of day and day in the week have been revealed.

The statistical distributions of magnitude and duration of voltage disturbances at rural sites has been presented also.

Chapter 4 Power Quality Profile of Rural Group

To assess the rural power quality, this chapter will present the graphic comparison between rural site voltage disturbances and the ITI power quality envelope curve and examine their compliance. The power quality profile of an individual rural site will be discussed first. Then all rural sites monitored will be combined into a single group and the power quality profile of rural group will be summarized.

4.1 Compliance with Power Quality Envelope

As introduced in the section 1.3.1, ITI curve is the successor of the CBEMA curve. It has been derived empirically to represent the intensity and duration of bus voltage disturbances that can be tolerated by most computers. The ITI curve illustrates the susceptibility of computers to voltage disturbances. If a voltage disturbance falls within the power quality envelope, no damage will be done to the computers. Thus, the disturbance can be treated as ignorable. Otherwise, if the voltage disturbance falls outside the power quality envelope, they might cause damage to the computers or an interruption of their normal operation, a costly loss to rural society.

From this point of view, two questions become our concerns when accessing rural power quality:

1. Are there any voltage disturbances exceeding the ITI curve limits and maybe disruptive or damaging to computers at a specific rural site?
2. How many voltage disturbances may be disruptive or damaging to computers at a specific site? How many are they for the rural group?

4.2 Individual Site Power Quality Profile

To answer the above questions, each encountered voltage disturbance will be plotted as a point on the ITI curve at a single rural site. The plot is intended to convey a sense of whether the recorded disturbances may be disruptive or damaging to sensitive electronic loads, like computers. However, in fact, the effect of the violations (voltage disturbances that exceed the ITI limits either in magnitude or duration or both) are depends very much on the design of the individual piece of equipment being subjected to the disturbance. Similar work has been done by [4]. At that time, the CEBMA curve was used.

4.2.1 Voltage surges with negative magnitude

As mentioned in Chapter 3, voltage surges consist of more than 55% of total rural power disturbances monitored. It is critical to express voltage surges properly to reach correct conclusions on rural power quality. One problem is that the power quality susceptibility curve is in logarithmic coordination, on which disturbance with zero or negative

magnitude cannot be plotted. However, the magnitude of voltage surges can be either positive or negative in the CEA survey. Actually there are 61.5% of voltage disturbances have negative magnitude in the survey.

Let us see how the magnitude of voltage surges was calculated. The BMI monitors record the surges as the peak voltage that they reached with the 60Hz. fundamental stripped off. It also reports the peak surge voltage, the surge phase position on the 60Hz. fundamental waveform, and the estimated energy content. The surge magnitude was calculated as deviation from the nominal (100%) voltage level. If the surge itself adds to the 60Hz waveform, the surge magnitude is added to the 100% nominal voltage level. If the surge subtracts from the 60Hz waveform, the surge magnitude is subtracted from the 100% nominal level. In summary, the surge magnitude is either added to or subtracted form the 100% nominal level, depending on whether the surge itself adds to or subtracts from the 60Hz waveform.

For instance, a surge with a negative peak voltage of 178V actually occurred during the positive 60Hz half cycle, therefore its magnitude was calculated as 100% - (178Vpeak/170Vpeak) × 100% = -5%. Peak b) as illustrated in Figure 4-1.

How to count these negative voltage surges is still controversial. One opinion is simply ignoring them because they are not included in the ITI curve. The other opinion is taking the absolute value of the negative voltage surges. Both points of view have their disadvantages. The first underestimates the number of negative surges. The second

overestimates the negative surges within the range from –1% to –100% when they still have normal voltage level. For example, peak c) in Figure 4-1 shows a positive surge occurred during the negative 60 Hz half cycle, which magnitude is less than –100%, but its actual voltage reaches not much above the positive fundamental voltage peak.

With reference to the monitor threshold setting of surges, 150Vpeak (approximately 88% of nominal peak voltage), negative surges with a magnitude less than –188% will be plotted as their absolute value in the power quality profile in this thesis.

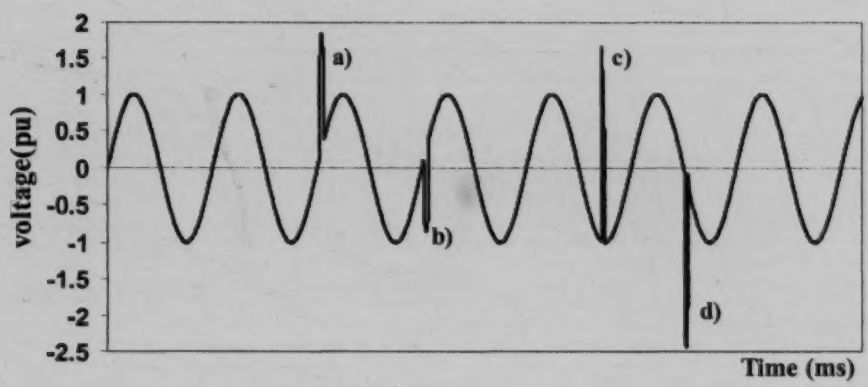


Figure 4-1 Positive & Negative Voltage Surges

4.2.2 Single site power quality envelope

Figure 4-2 show the power quality profile of Site 0298. Though there are only 22 disturbances captured during the month monitored, 4 of them, about 20% of total disturbances, are outside the power quality envelope. Among them, one transient falls

into the prohibited region, which means that damage may result to the computers at this site. The other three violations are waveshape faults. They fall into the no damage region, which means that interruption of function may occur to computers though there is no damage to equipment.

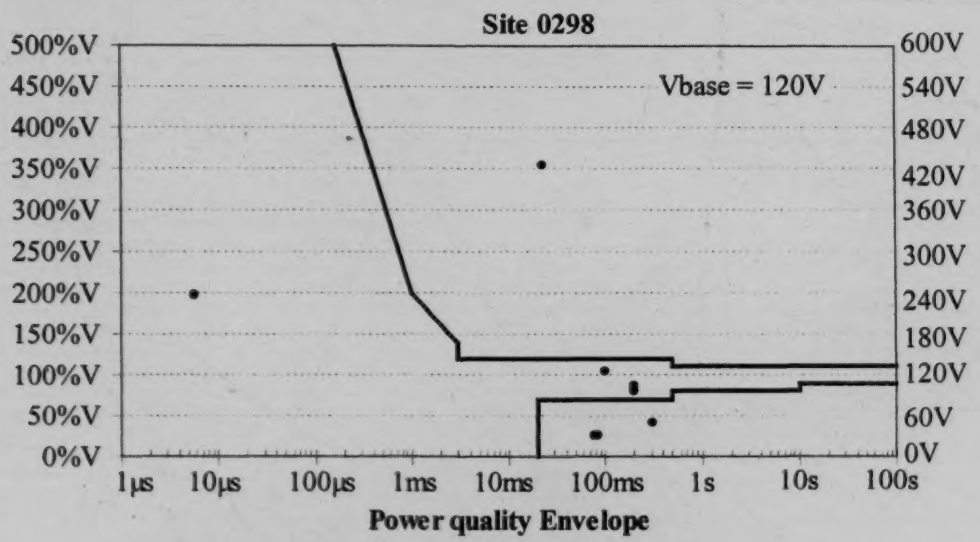


Figure 4-2 Individual Site Power Quality Profile at Site0298

4.3 Rural Group Power Quality Profile

4.3.1 Rural group steady-state voltage histogram

The supply voltage was monitored and recorded for each rural site for a period of 31 days on average at the customer's service entrance panel (e.g., 120/240V). The voltage profile for an individual site has already been described in Section 2.1.

Figure 4-3 shows the steady-state voltage histogram for all the 69 rural sites as a group. It gives a comprehensive view of rural rms supply voltage levels at the rural customer service entrance. The variations in the rms supply voltage levels as well as the variations limits are clearly revealed in the histogram.

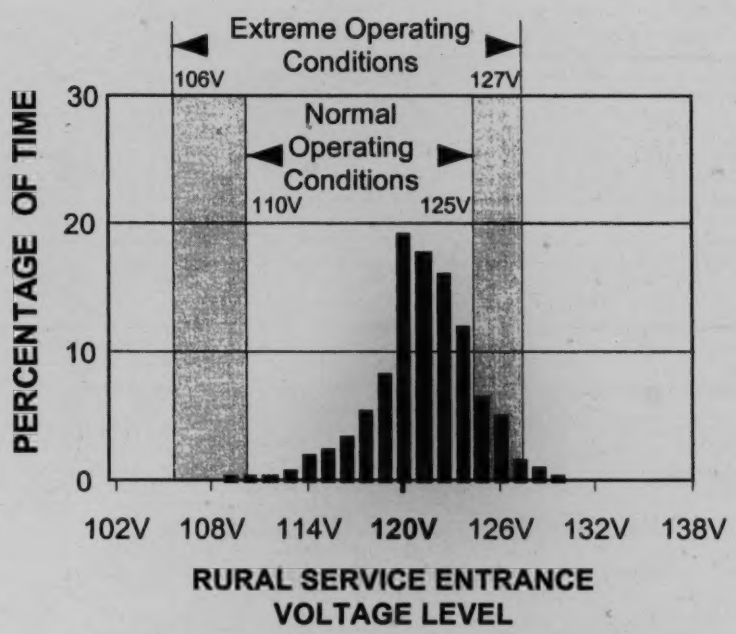


Figure 4-3 Rural Group Steady-state Voltage Histogram

The average supply voltage of all the rural sites and its %THD is shown in Table 2.

Table 4-1. Steady-state voltage Supply statistical characteristics

Voltage Parameter	Characteristic
Total Monitoring Time:	74,756.70 Channel*hrs
Average Voltage:	120.12 V

Table 4-2 shows the percentage of the time the rural group supply voltage resides in the normal and extreme operating conditions which are defined by the CAN3-C235-83 Standard.

Table 4-2 Percentage of Time the Service Entrance Voltage Level is within and outside CSA Boundaries

	LOWER LIMIT	OPERATING RANGE	UPPER LIMIT
	<110V	NORMAL OPERATING CONDITIONS 110-125V	>125V
% OF TIME	0.21%	92.44%	7.35%
	<106V	EXTREME OPERATING CONDITIONS 106-127V	>127V
% OF TIME	0.02%	98.99%	0.99%

The average voltage monitored at the rural sites was 101.1% of nominal voltage (i.e., 120.12 V). However, 7.35% of the time the voltage would be in the CSA Extreme Operating Conditions which was greater than 104.2 % of the nominal voltage, significantly demonstrating that the voltage levels at rural sites rise to levels outside the normal operating conditions.

4.3.2 Rural group power quality profile

All the power supply disturbances occurred at the CEA survey rural sites are grouped and plotted in Figure 4-4 with the ITI curve. Most of the disturbances fell within either the

"Voltage Tolerance Region" which is applicable to single phase 120V equipment or the "No Interruption in Function Region". There were a few surges within the Prohibited Region. Some waveshape faults and voltage sags were within the No Damage Region. They caused equipment function interruption, and damage might be caused depending on the particular condition.

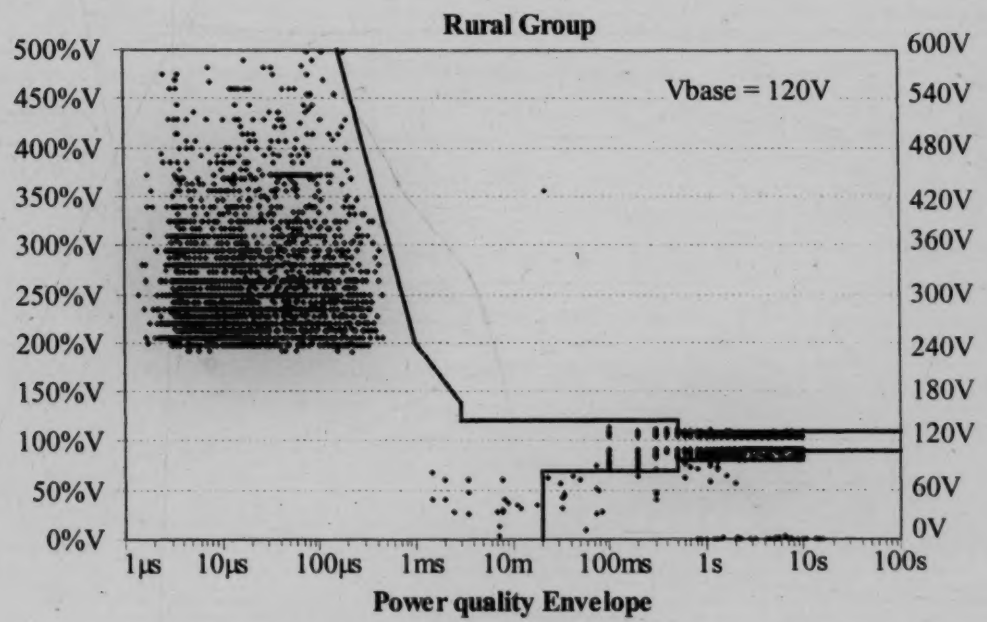


Figure 4-4 Rural Group Power Quality Profile

4.4 Rural group cumulative probability contours

Group cumulative probability contours have been used in [20, 21]. They provide a more comprehensive picture of power quality than the seminal power quality surveys [22, 23] could produce with data from the early generation of power quality line monitors.

The relative cumulative contours were applied by Conrad in [21], where the contours show the percentage of events recorded. Such contours are independent of the monitor thresholds used. So data from different surveys are comparable.

The absolute sense contour lines were used in [20] by M. Brent Hughes and John S. Chan, where the contours show the cumulative probability of events per month. They may be useful to the equipment manufactures in deciding how much immunity to build into their products because the contours show the actual number of events that can be expected. For example, they can pick a misoperation or failure rate they and the customers can accept, then refer to the corresponding contour line to determine the level of built-in immunity required to achieve that failure rate. This project investigates the absolute contours of the rural data.

4.4.1 Scale factor

This scale factor is the effective per month, per channel value of each individual disturbance for that site, through which the voltage transient disturbance activity for each rural site was normalized and averaged to a per channel, per month basis. The scale factor for each site was defined as below [20]:

$$\text{Scale factor} = \frac{\text{Average channel*hours per month}}{\text{Site channel*hours recorded}}$$

The scale factors can be calculated according to the definition with the average number of 613.21 channel*hours per month for rural sites. Result is shown in Table 4-3.

Table 4-3 CEA Rural Site ID & Corresponding Scale Factor

CEA Site ID	Scale Factor	CEA Site ID	Scale Factor	CEA Site ID	Scale Factor
SITE0015	0.43	SITE0235	0.46	SITE0443	0.52
SITE0034	0.60	SITE0252	0.88	SITE0444	0.50
SITE0037	0.54	SITE0271	0.50	SITE0446	0.44
SITE0052	0.46	SITE0272	0.33	SITE0454	0.39
SITE0056	0.47	SITE0278	0.40	SITE0459	0.60
SITE0064	0.80	SITE0281	0.45	SITE0478	0.82
SITE0073	0.44	SITE0282	0.40	SITE0479	0.50
SITE0082	0.44	SITE0285	0.44	SITE0488	0.48
SITE0091	0.80	SITE0288	0.41	SITE0515	0.85
SITE0103	1.49	SITE0298	0.91	SITE0523	0.67
SITE0112	0.37	SITE0324	0.74	SITE0535	0.55
SITE0124	0.44	SITE0329	0.54	SITE0539	0.76
SITE0128	0.75	SITE0398	0.99	SITE0541	1.91
SITE0148	0.79	SITE0399	0.84	SITE0543	0.41
SITE0166	0.98	SITE0411	0.38	SITE0600	0.47
SITE0167	0.90	SITE0423	0.49	SITE0605	0.73
SITE0168	0.84	SITE0424	0.48	SITE0616	2.12
SITE0169	0.41	SITE0425	0.35	SITE1018	0.71
SITE0175	0.46	SITE0428	1.55	SITE1042	0.59
SITE0206	0.70	SITE0432	0.44	SITE1080	3.12
SITE0213	0.90	SITE0433	0.42	SITE1083	0.36
SITE0218	1.02	SITE0437	0.47	SITE1086	1.16
SITE0234	0.53	SITE0438	0.46	SITE1092	0.55

4.4.2 Voltage sag contours

Multiplied by their scale factors, the disturbance data from different sites were weighed to the per channel, per month basis and then could be added up as the effective per month, per channel value of each individual disturbance for that site.

The power quality envelope was divided up into a grid, and the effective values of all the voltage sags that fall into each grid element was summed, averaged and finally the cumulative event exposure probability was calculated. Contour lines were drawn linking points of equal event probability. The contours show the cumulative probability of encountering voltage sags as or more severe that the point being considered on the power quality envelope. Here more severe means voltage sag with lower magnitude, longer duration, or both.

The rural group voltage sag contours are shown in Figure 4-5. The colorful contour lines correspond to different cumulative sag exposure probabilities. For instance, the 0.1 sag/month contour is red. It passes through the 72% nominal voltage, 1 s point on the power quality envelope, this means that there is a 0.1 event/month probability of encountering a voltage sag with this or lower voltage and this or longer duration.

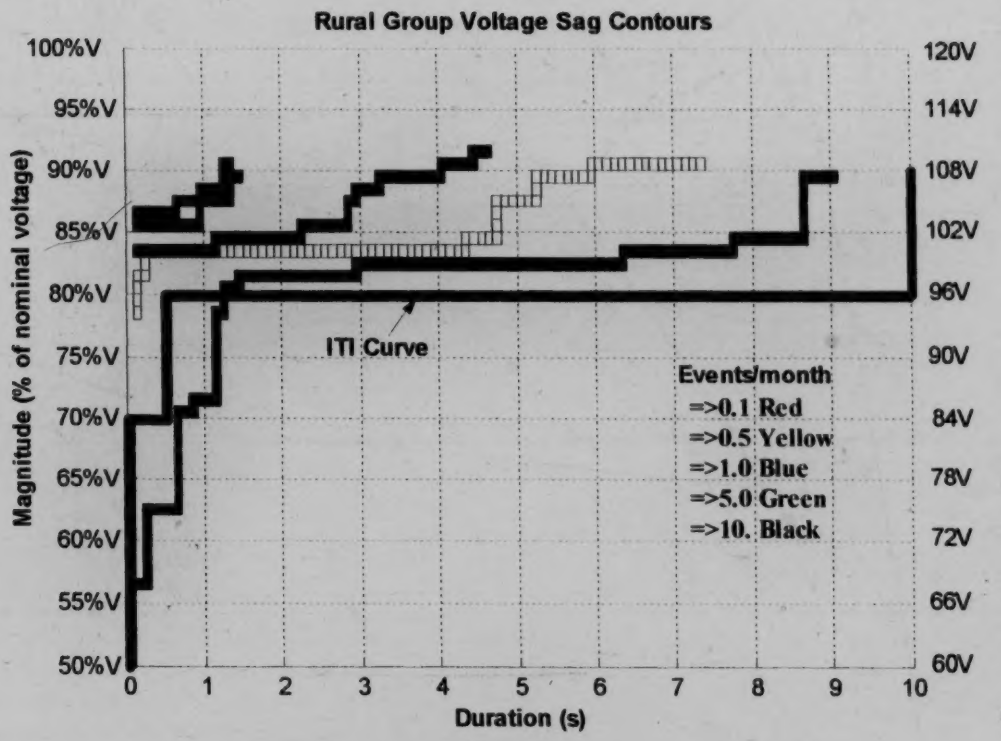


Figure 4-5 Rural Group Voltage Sag Contours

Partial of the ITI Curve is plotted in Figure 4-5. It is obvious that part of the 0.1 event/month contour line is outside the ITI Curve.

4.4.3 Voltage swell contours

The effective values of all the voltage swells were summed using a grid structure, averaged and finally the cumulative event exposure probability contours were drawn. The contours show the cumulative probability of encountering voltage swells as or more severe that the point being considered on the power quality envelope. Here more severe means a disturbance with higher magnitude, longer duration, or both.

The rural group voltage swell contours are shown in Figure 4-6. The colorful contour lines correspond to different cumulative event exposure probabilities. In a way of example, the 0.5 event/month contour is yellow. It passes through the 108% nominal voltage, 1.1 s point on the power quality envelope, this means that there is a 0.5 event/month probability of encountering a voltage swell with this or higher voltage and this or longer duration.

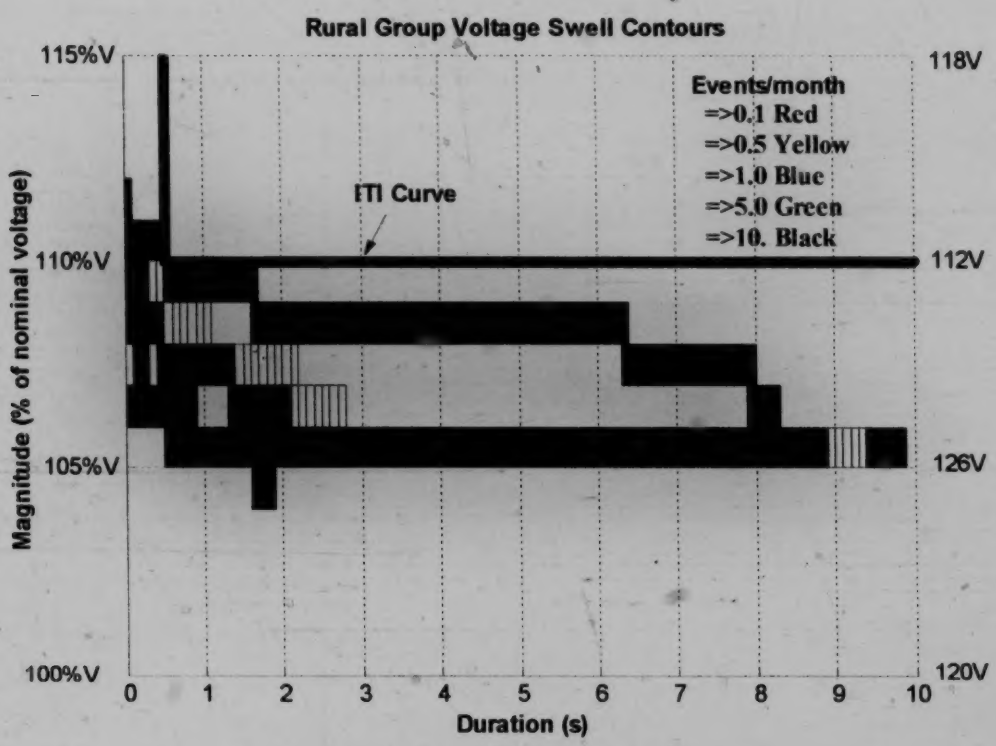


Figure 4-6 Rural Group Voltage Swell Contours

Partial of the ITI Curve is plotted in Figure 4-6. It is observed that part of the 0.1 event/month contour line borders upon the ITI Curve. All voltage swell contours fall within the ITI Curve.

4.4.4 Voltage surge contours

Voltage surges were the most frequently recorded event at rural sites. The effective values of all the voltage surges were also summed using a grid structure, averaged and finally their cumulative event exposure probability contours were drawn. The contours show the cumulative probability of encountering voltage surges as or more severe that the point being considered on the power quality envelope. Here more severe means a disturbance with higher magnitude, longer duration, or both.

The rural group voltage surge contours are shown in Figure 4-8. The contour lines correspond to different cumulative event exposure probabilities, as labeled on the figure. For example, the 0.1 event/month contour passes through the 400% nominal voltage, 0.135 ms point on the power quality envelope, this means that there is a 0.1 event/month probability of encountering a voltage surge with this or higher voltage and this or longer duration.

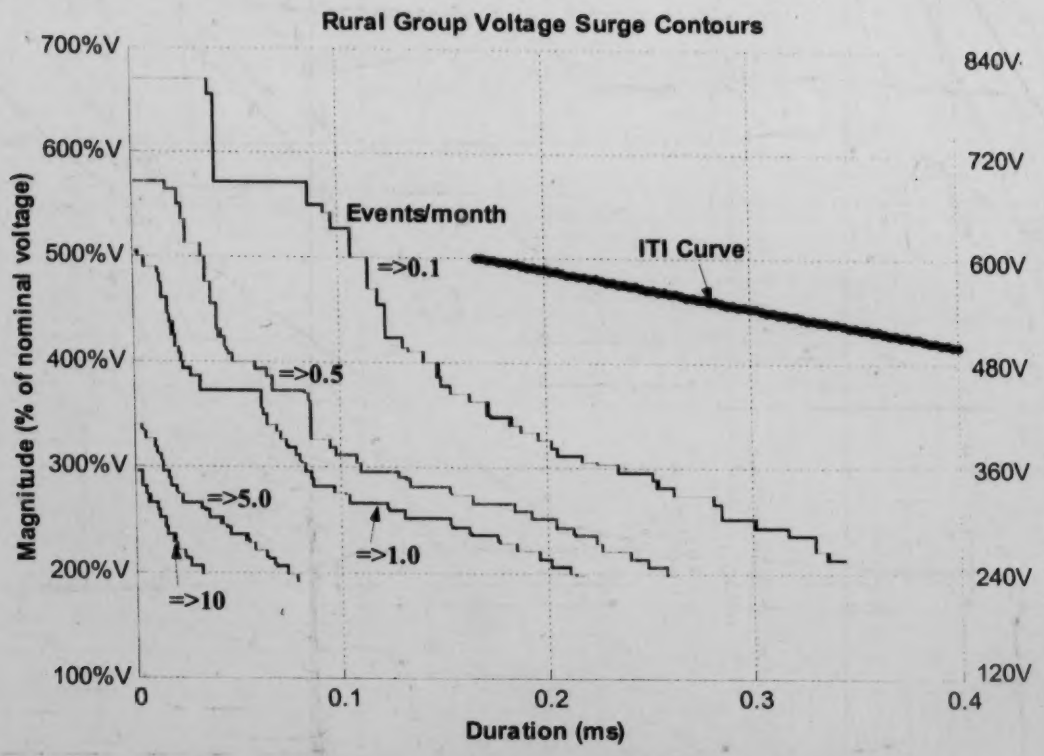


Figure 4-7 Rural Group Voltage Surge Contours

Partial of the ITI Curve is plotted in Figure 4-7. According to the ITI Curve, the surge limit with the highest voltage is 500% nominal voltage and lasting for 0.01cycle, 0.167ms. The contour lines show most of the surges lasted shorter than 0.167ms, and their magnitude were higher than 300% nominal voltage.

4.5 Define Canadian Rural Electric Environment

The CEA Power Quality Survey rural data has enabled a better understanding of the typical rural electrical environment within which sensitive electronic equipment must be able to operate. Utility protective and regulation devices, like reclosers, may cause

voltage variations. The load equipment operation may cause voltage variations too. They both contributed to the total power quality picture. Regardless of the origin of these variations, the rural end use electrical and electronics equipment must be able to operate with some degree of immunity. The CEA Power Quality Survey rural data has been assessed to define the rural electrical environment.

4.5.1 The rural electric environment based on the CEA survey

The CEA survey was carried out from 1991 to 1994. The rural voltage disturbance data has been averaged into per month. Table 4-4 displays the number of recorded low RMS voltage disturbance events per month in rural area according to CEA survey. All recorded events for each block are included in the table.

Table 4-4 CEA Rural Power Supply Low RMS Disturbance per Month

Mag. vs Dur.	1 ~ 6 cy.	6~10 cy.	10~20 cy.	20~30 cy.	0.5 ~ 1 sec.	1 ~ 2 sec.	2 ~10 sec.	>10 sec.	Average No. of Events
> 110%	0.01	0.00	0.01	0.02	0.01	0.01	0.00	0.00	0.06
106% ~ 110%	3.03	0.00	4.70	5.50	7.70	3.00	1.01	0.00	24.94
80% ~ 90%	0.51	0.00	5.47	3.32	11.04	16.66	1.87	0.00	38.87
70% ~ 80%	0.12	0.00	0.21	0.00	0.04	0.03	0.00	0.00	0.40
50% ~ 70%	0.06	0.00	0.02	0.00	0.01	0.02	0.02	0.00	0.13
10% ~ 50%	0.11	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.14
0% ~ 10%	0.01	0.00	0.00	0.00	0.00	0.01	0.04	0.00	0.06
Average No. of Events	3.85	0.00	10.44	8.84	18.80	19.73	2.94	0.00	64.60

Examining Table 4-4 voltage sags with magnitude ranging from 80% ~ 90% nominal voltage and voltage swells with magnitude from 106% ~ 110% nominal voltage and lasted 10 cycles to 2 seconds were the majority of the Canadian rural low RMS voltage disturbances.

Table 4-5 displays the number of recorded high RMS voltage disturbance events per month for the CEA Power Quality Survey rural data.

Table 4-5 CEA Rural Power Supply High RMS Disturbance per Month

Mag.vs Dur.	1 ~ 10 μs	10μs ~ .001cy.	.001~ .01cy.	.01cy. ~1ms	1 ~ 3 ms	3ms ~ 1cy.	Average No. of Events
1100~ 700%	0.01	0.00	0.11	0.00	0.00	0.00	0.12
700 ~ 600%	0.01	0.01	0.09	0.00	0.00	0.00	0.11
600 ~ 500%	0.05	0.18	0.53	0.04	0.00	0.00	0.80
500 ~ 400%	0.19	0.29	0.48	0.01	0.00	0.00	0.97
400 ~ 300%	2.29	0.98	1.49	0.20	0.00	0.00	4.96
300 ~ 200%	74.60	5.78	7.87	1.39	0.00	0.00	89.64
200 ~ 100%	0.28	0.16	0.81	0.14	0.01	0.00	1.40
100 ~ 0%	6.00	0.57	0.47	0.14	0.05	0.11	7.34
0 ~ -100%	120.42	9.37	8.90	1.39	0.03	0.02	140.13
-100 ~ -200%	2.22	1.41	2.49	0.35	0.01	0.00	6.48
-200 ~ -300%	0.30	0.21	1.31	0.12	0.00	0.00	1.94
-300 ~ -400%	0.07	0.11	1.28	0.02	0.00	0.00	1.48

Table 4-5 CEA Rural Power Supply High RMS Disturbance per Month (Continued)

Mag.vs Dur.	1 ~ 10 μs	10μs ~ .001cy.	.001~ .01cy.	.01cy. ~1ms	1 ~ 3 ms	3ms ~ 1cy.	Average No. of Events
-400 ~ -500%	0.01	0.00	0.09	0.01	0.00	0.00	0.11
-500 ~ -700%	0.01	0.00	0.01	0.00	0.00	0.00	0.02
Average No. of Events	206.46	19.07	25.93	3.82	0.10	0.13	255.50

Examining Table 4-5 voltage surges with magnitude ranging from 200% ~ 300% and 0% ~ -100% nominal voltage lasting 1 ~ 10 us were the majority of the Canadian rural high RMS voltage disturbances. Surges of 200% ~ 300% and 0% ~ -100% nominal voltage both had peak voltages within 170V ~ 340V after striping from the fundamental voltage wave, but they had different directions. Positive surges added to the fundamental voltage, while negative surges subtract from the fundamental. It should be noted that negative surges occurred more often than positive ones.

The above assessment displayed the majority of rural voltage disturbance were within the ITI "No Interruption in Function Region ". Rural load equipment with reasonable voltage regulation and interruption ride-through will withstand the majority of recorded power-line variations.

4.5.2 Comparison with other customer groups in the CEA survey

Compared with other customer groups, including the feeder, industrial, commercial and residential groups, in the CEA Survey, the rural group has its own characteristics. Table 4-6 shows the statistical voltage disturbance occurrence frequency, voltage THD, voltage variations and average voltage of each group.

Table 4-6 Power Quality Profile of Various Sites Covered by Canada Wide Surveys.

Disturbance Type	Feeder	Industrial Sites	Commercial Sites	Residential Sites	Rural Sites
Transients (#/month)	10	44	153	213	**221**
Waveshape fault (#/month)	1	2	4	2	**2**
Swell (#/month)	68	73	144	122	**154**
Sag (#/month)	3	28	5	35	**36**
Interruption (#/month)	<1	<1	<1	<1	**<1**
Voltage THD (%)	1.5	1.6	2.0	1.6	**1.6**
Over voltage (% time > 104%)	7.3	3.9	6.7	4.8	**7.35**
Under voltage (% time < 92%)	0.2	1.2	0.1	0.2	**0.21**
Average voltage (% of 120V)	101	100	101	101	**101.4**

As shown in Table 4-6, the rural sites generally experience more transients and short-duration variation disturbances. How to mitigate these types of disturbances would, therefore, be of primary importance to rural coops.

The harmonic distortion levels at rural sites are comparable to the system average. It means that rural customers generally don't cause additional distortions in the system. Consequently, harmonics appear not to be a general concern for rural co-ops.

In terms of long term average voltage profile, the rural sites are also similar to other sites. This implies that the operation of rural feeders is, on average, generally comparable with their urban counter parts. It was noted however that the steady-state voltages in rural sites have larger variations.

Also, disturbances recorded for other customer groups have been digitized from their contours in [20]. The digitalized results of the low voltage disturbances of other customer types are tabulated in Appendix D. Comparisons have been carried out to the average number of the monthly low RMS disturbances between different groups, which are shown in Figure 4-8 to Figure 4-10.

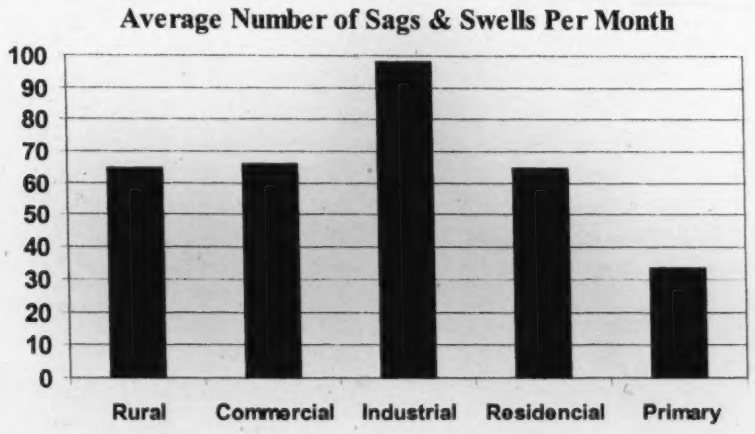


Figure 4-8 Comparison of Average Number of Disturbances Per Month

Figure 4-8 indicates that the industrial customers have the most number of voltage sags and swells per month, followed by the commercial and rural customers. The average numbers of monthly disturbances were similar among the commercial, residential and rural groups, and their monthly low RMS disturbance occurrence was 2/3 of the industrial. The primary sites have the least number of disturbances. The average number of low RMS disturbances per month occurred at the primary sites was only 1/2 of those of the commercial & rural, and 1/3 of that of the industrial.

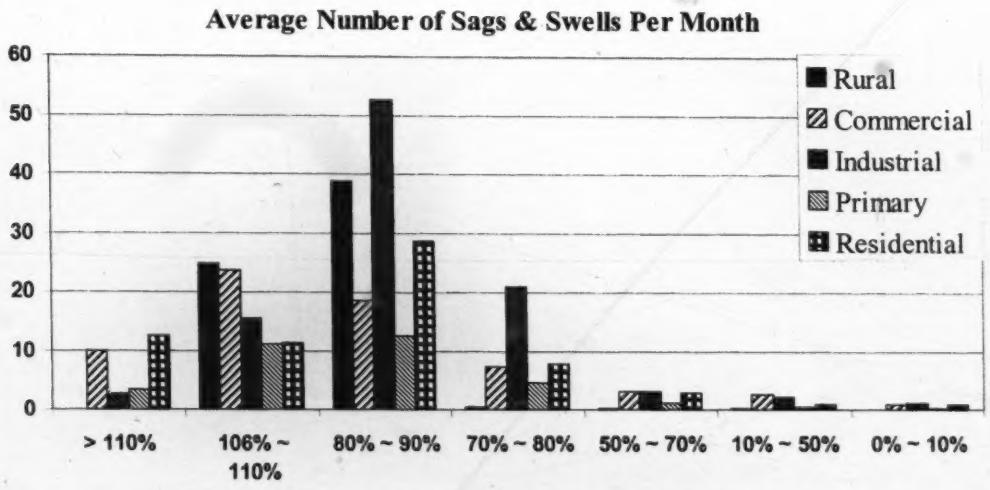


Figure 4-9 Average Number of Disturbances Per Month by Magnitudes

Comparison has also been made to the monthly average number of voltage sags and swells divided by their magnitude among different customer groups, which is shown in Figure 4-9. Most of voltage sags recorded at industrial and rural sites had the magnitude of 80~90% of the nominal voltage. The industrial had the most sags, and then followed by the rural, the residential, the commercial, and the primary. The industrial customers also had over 20 sags per month with the magnitude of 70~80% of the nominal voltage, which were mainly caused by the motors' starting.

About the voltage swells with the magnitude of 106~110% of the nominal voltage, there were considerably swells within this magnitude range occurred at rural, then comes the commercial, the industrial, the residential and the primary. The residential and

commercial customers had about 10 swells per month with the magnitude over 110% of the nominal voltage.

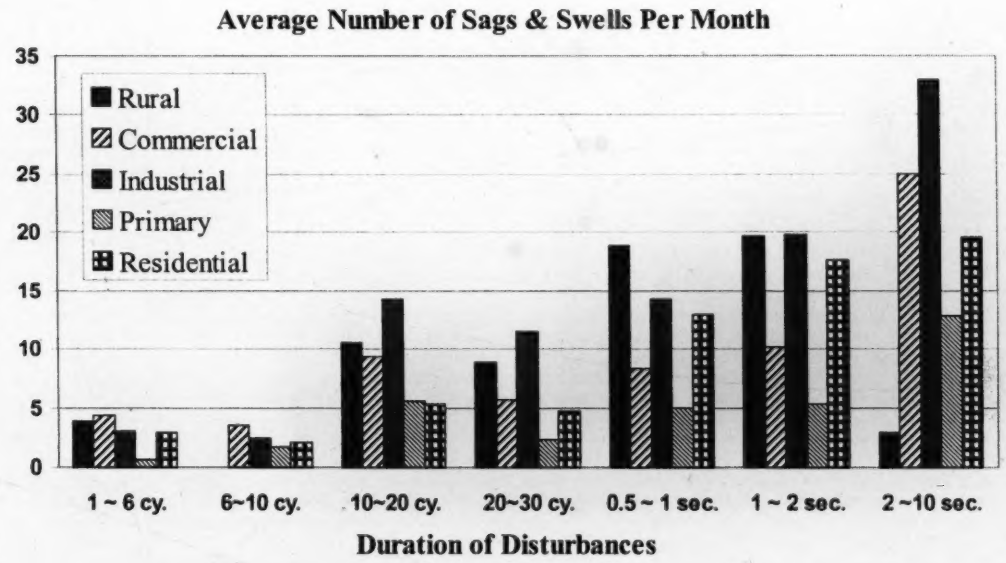


Figure 4-10 Average Number of Disturbances Per Month by Durations

Figure 4-10 illustrates the comparison among different types of customers on the average number of voltage sags and swells occurred per month. The disturbances in each customer group are grouped according to their duration. The rural customers had more low RMS disturbances lasting within 0.5~2 s. The industrial and commercial customers had most disturbances that lasted longer than 2 s.

In summary, the primary sites had the best power quality. The average numbers of voltage sags and swells per month were comparably at the rural, commercial and residential sites. The industrial sites had the most sags and swells. The average number of

voltage sags and swells occurred at the industrial was near 1.5 times of that of the rural, commercial and residential. However, more rural low RMS disturbances had shorter duration and magnitude near the nominal than those at the industrial, commercial, and residential sites.

The disturbances that lasted less than 1 cycle have not been compared. Because the shortest duration threshold of recorded voltage sags and swells were 80 ms, the disturbances lasting less than 1 cycle were mainly voltage surges. Part of the negative voltage surges (magnitude smaller than –1.88pu) was counted in the contours in this chapter as their absolute value. However, all the negative voltage surges were dumped on the X-axis in the contours in [20]. Due to the difference in the treatment of negative surges, a comparison between the CEA rural surges and those of other customer groups was not possible.

4.6 Conclusions

The events explosion contours of voltage sags, voltage swells and voltage surges are drawn and compared with the ITI power quality subspecialty curve to check their compliance. The power quality characteristics of the rural have been compared with those of other customer groups (industrial, commercial and residential) in the CEA survey, and the rural electric environment has been defined.

Chapter 5 Conclusions

Rural electric power quality has not been throughly studied. With more computer like equipment being used in rural area, there is increasing need to carry out power quality assesment specially for the rural customers. This thesis has investigated power quality of 69 rural sites in Canada based on the data of the CEA National Power Quality Survey and presented the findings. It enables a better understanding of the rural electrical environment and provides the knowledge base for utilites and rural customers to choose miligation measures. Also, the profiles can be used for designing rural computers, controllers and mitigating devices.

The long term steady-state voltage profile of each rural site has been invegistated and compared with the CAN3-C235-83 Standard accordingly, including the voltage levels at the service entrance and those at the utilization point. Shows where utilities can improve service by using transformer taps or feeder regulator to shift the voltage profile. The minimal, maximal and average voltage of each site has been ranked and tabulated. It has been revealed that the rural voltage level dwelled in the "extremly overvoltage range" for a considerable period of time. No apparent evidence shows that the feeder length affected rural site long term steady-state voltage levels directly.

The statistical characteristics of rural voltage disturbances have been presented. Voltage surges, voltage swells and votlage sags were the majority of the diturbances rural electric experienced. Their occurrence parterns as a function of the time of day and day in the week have been revealed.

The voltage sags daily pattern tends to follow the daily loading patterns of the utility, i.e., the utilities response to changing demands appears to cause more voltage sags at certain times of the day.

The occurrence of voltage swells and surges appear to be uniformly distributed during the week. However, application of the Chi-square test, voltage swells and surges could not be represented by a uniform distribution. Voltage sags tended to occur more frequently during the weekdays than on the weekends.

The statistical distributions of magnitude and duration of voltage disturbances at rural sites has been presented also.

Most voltage sags have a magnitude between 87% and 92% of nominal voltage and most of them last for a duration less than 1 second. For voltage swells, most of them had a magnitude 104% or 105% of the nominal voltage and the duration ranges from 0.1 s to 1 s.

For the positive voltage surges, 87.3% of them fall into the mangitude range from 200%

to 300% of the nominal voltage and 86.1% of the positive voltage surges lasted from 1 μs to 15 μs. For negative voltage surges, 93.4% of the total ranges from -5% to -100% of the nominal voltage in mangitude and 88.8% of the negative voltage surges lasted from 1us to 15 μs in duration.

The power quality of rural group has been summarized. For all rural sites the average long term rural steady-state voltage was 101.1% of nominal, which is quite acceptable. However, about 7% of the time the rural voltage levels were outside the normal operating range (i.e., > 125 V) specified by CSA. The high operating voltage levels can significantly shorten the life of motors and lighting equipment, a concern for rural communities.

The contour lines of voltage sags, voltage swells and voltage surges linked the points with the same events explosion. Compared with the ITI power quality subspecialty curve, part of the 0.1 event/month contour line is outside the ITI Curve for voltage sags. Voltage swells and surges had the contour in compliance with the ITI Curve.

Compared to other customer groups (industrial, commercial and residential) in the CEA survey, the rural power quality has the following characteristics:

- Generally experience more voltage surges (more than 50% of the total disturbances recorded) and short-duration variation disturbances. How to mitigate

these types of disturbances would, therefore, be of primary importance to rural customers.

- The harmonic distortion levels at rural sites are comparable to the system average. It means that rural customers generally don't cause additional distortions in the system. Consequently, harmonics appear not to be a general concern for rural customers.
- In terms of long term average voltage profiles, the rural sites are similar to other sites. This implies that the operation of rural feeders is, on average, generally comparable with their urban counter parts. It was noted however that the steady-state voltages in rural sites have larger variations.

The thesis has intended to define the Canadian rural electrical environment in which rural electronic and electrical equipment must operate based on the rural site data from the CEA survey. More investigation need to be carried out particularly for rural sites to better describe the recent rural electrical supply environment.

The statistical characteristics revealed by this thesis provide knowledge base for miligating thechnologies. However, considerably more research is required to determine with some certainty the possible underlying statistical distributions that can represent the voltage disturbances occurring at rural sites.

APPENDIX A: CHI-AQUARE TEST

A.1. Chi-square test for voltage sags' daily distribution in a week

A Chi-square test was performed to examine the daily distribution of voltage sags in a week was uniformly or not.

Similar with the Chi-square test for voltage swells described in full length in the Chapter 3, hypothesize that voltage sags were distributed uniformly in a week and therefore that H_0: $p_1 = p_2 = p_3 = p_4 = p_5 = p_6 = p_7 = 1/7 = 14.28\%$. The total number of voltage sags is 1123 and the expected daily count is 1123/7 = 160.43. Here, H_0 denotes the null hypothesis, and p_i represents the possibility of swells occurring on a specific day in a week, i = 1, 2, 3, 4, 5, 6, 7 (starting from Sunday to Saturday). The observed and expected daily frequencies are presented in Table A-1.

Table A-1. Observed and Expected Daily Sags Counts

	1	2	3	4	5	6	7
Observed Daily Frequency	122	159	186	155	256	148	97
Expected Daily Frequency	160.43	160.43	160.43	160.43	160.43	160.43	160.43

Since the only restriction on the observations is that $\sum_{i=1}^{7} p_i = 1$, the Chi-square test will possess (7-1) = 6 degrees of freedom. Therefore, if we chose $\alpha = 0.05$ (α denotes the

possibility of Type I error), the null hypothesis will be rejected when $X^2 > 12.5916$ according to the table of Critical Values of Chi-square.

Substituting into the formula for X^2, we obtain $X^2 = \sum_{i=1}^{7} \frac{[p_i - E(p_i)]^2}{E(p_i)} = 96.45$. For voltage sags, the X^2 (96.45, 6) is much greater than the critical Chi-square value (12.59, 6) and the hypothesis that voltage sags are distributed uniformly during each day in a week has been rejected.

A.2. Chi-square test for voltage surges' daily distribution in a week

Hypothesize that for the daily occurrence pattern of voltage surges were distributed uniformly in a week and therefore that H_0: $p_1 = p_2 = p_3 = p_4 = p_5 = p_6 = p_7 = 1/7 = 14.28\%$. The total number of voltage swells is 19918 and the expected daily count is 19918/7 = 2845.43. Here, H_0 denotes the null hypothesis, and p_i represents the possibility of swells occurring on a specific day in a week, i = 1, 2, 3, 4, 5, 6, 7 (starting from Sunday to Saturday). The observed and expected daily frequencies are presented in Table A-2.

Table A-2. Observed and Expected Daily Surges Counts

	1	2	3	4	5	6	7
Observed Daily Frequency	2870	2818	2997	2666	2763	2883	2921
Expected Daily Frequency	2845.4	2845.4	2845.4	2845.4	2845.4	2845.4	2845.4

Since the only restriction on the observations is that $\sum_{i=1}^{7} p_i = 1$, the Chi-square test will possess (7-1) = 6 degrees of freedom. Therefore, if we chose $\alpha = 0.05$ (α denotes the possibility of Type I error), the null hypothesis will be rejected when $X^2 > 12.5916$ according to the table of Critical Values of Chi-square.

Substituting into the formula for X^2, we obtain $X^2 = \sum_{i=1}^{7} \frac{[p_i - E(p_i)]^2}{E(p_i)} = 24.76$. X^2 (24.76, 6) is greater than the critical Chi-square value (12.59, 6) and the hypothesis that voltage surges are distributed uniformly during each day in a week has been rejected.

APPENDIX B: Tables Corresponding CEA rural site ID to the ordered number

Table B-1. Corresponding CEA Site ID to the Ordered Number Sorted by the Frequency of Voltage Sags in Figure 3-2

CEA Site ID	Number	CEA Site ID	Number	CEA Site ID	Number
SITE1018	1	SITE0433	24	SITE0423	47
SITE0543	2	SITE0281	25	SITE0399	48
SITE0535	3	SITE0112	26	SITE0128	49
SITE0478	4	SITE0052	27	SITE1042	50
SITE0438	5	SITE0541	28	SITE0124	51
SITE0428	6	SITE0446	29	SITE0605	52
SITE0285	7	SITE0298	30	SITE0539	53
SITE0278	8	SITE0272	31	SITE0424	54
SITE0271	9	SITE0206	32	SITE0082	55
SITE0169	10	SITE0064	33	SITE0148	56
SITE0034	11	SITE0398	34	SITE1092	57
SITE1086	12	SITE0288	35	SITE0213	58
SITE0616	13	SITE0218	36	SITE0073	59
SITE0515	14	SITE0168	37	SITE0479	60
SITE0459	15	SITE0015	38	SITE0523	61
SITE0443	16	SITE0324	39	SITE0432	62
SITE0425	17	SITE0600	40	SITE0175	63
SITE0411	18	SITE1083	41	SITE0488	64
SITE0282	19	SITE0329	42	SITE0235	65
SITE0252	20	SITE0166	43	SITE0037	66
SITE0167	21	SITE0091	44	SITE1080	67
SITE0103	22	SITE0056	45	SITE0234	68
SITE0437	23	SITE0444	46	SITE0454	69

Table B-2. Corresponding CEA Site ID to the Ordered Number Sorted by the Frequency of Voltage Swells in Figure 3-9

CEA Site ID	Number	CEA Site ID	Number	CEA Site ID	Number
SITE1092	1	SITE0175	24	SITE0459	47
SITE0433	2	SITE0438	25	SITE0056	48
SITE0423	3	SITE0543	26	SITE0073	49
SITE0235	4	SITE1083	27	SITE0444	50
SITE0213	5	SITE0523	28	SITE0478	51
SITE0128	6	SITE0424	29	SITE0437	52
SITE0064	7	SITE0285	30	SITE1042	53
SITE0539	8	SITE0281	31	SITE1080	54
SITE0411	9	SITE0278	32	SITE0282	55
SITE0124	10	SITE0052	33	SITE0091	56
SITE0015	11	SITE0428	34	SITE1018	57
SITE0454	12	SITE0399	35	SITE0082	58
SITE0298	13	SITE0166	36	SITE0425	59
SITE0234	14	SITE0446	37	SITE0605	60
SITE0432	15	SITE0329	38	SITE0535	61
SITE0398	16	SITE0206	39	SITE1086	62
SITE0252	17	SITE0616	40	SITE0324	63
SITE0271	18	SITE0272	41	SITE0034	64
SITE0112	19	SITE0515	42	SITE0541	65
SITE0148	20	SITE0600	43	SITE0218	66
SITE0479	21	SITE0168	44	SITE0443	67
SITE0288	22	SITE0488	45	SITE0167	68
SITE0169	23	SITE0037	46	SITE0103	69

Table B-3. Corresponding CEA Site ID to the Ordered Number Sorted by the Frequency of Voltage Surges in Figure 3-15

CEA Site ID	Number	CEA Site ID	Number	CEA Site ID	Number
SITE0459	1	SITE1042	24	SITE0288	47
SITE0167	2	SITE0329	25	SITE0252	48
SITE0285	3	SITE0443	26	SITE0541	49
SITE0206	4	SITE0128	27	SITE0411	50
SITE0398	5	SITE0234	28	SITE0091	51
SITE0428	6	SITE0479	29	SITE0446	52
SITE0523	7	SITE0037	30	SITE0432	53
SITE0218	8	SITE1083	31	SITE0272	54
SITE0166	9	SITE0056	32	SITE0425	55
SITE0488	10	SITE0112	33	SITE0281	56
SITE0324	11	SITE0438	34	SITE0437	57
SITE0168	12	SITE0073	35	SITE1092	58
SITE0298	13	SITE0600	36	SITE0034	59
SITE0103	14	SITE0399	37	SITE0213	60
SITE0424	15	SITE0454	38	SITE0082	61
SITE0423	16	SITE0282	39	SITE0124	62
SITE0235	17	SITE1080	40	SITE0433	63
SITE0444	18	SITE0015	41	SITE0064	64
SITE0148	19	SITE0535	42	SITE0605	65
SITE0478	20	SITE0271	43	SITE0616	66
SITE1018	21	SITE0175	44	SITE0278	67
SITE0515	22	SITE0539	45	SITE0052	68
SITE0169	23	SITE1086	46	SITE0543	69

Table B-4. Corresponding CEA Site ID to the Ordered Number Sorted by the Frequency of Outages in Figure 3-22

CEA Site ID	Number	CEA Site ID	Number	CEA Site ID	Number
SITE1086	1	SITE0423	24	SITE0064	47
SITE1083	2	SITE0411	25	SITE0037	48
SITE1080	3	SITE0329	26	SITE0541	49
SITE1042	4	SITE0324	27	SITE0523	50
SITE1018	5	SITE0298	28	SITE0437	51
SITE0605	6	SITE0285	29	SITE0398	52
SITE0600	7	SITE0282	30	SITE0034	53
SITE0543	8	SITE0281	31	SITE0616	54
SITE0539	9	SITE0278	32	SITE0444	55
SITE0535	10	SITE0272	33	SITE0443	56
SITE0515	11	SITE0271	34	SITE0399	57
SITE0488	12	SITE0234	35	SITE0288	58
SITE0479	13	SITE0218	36	SITE0252	59
SITE0478	14	SITE0213	37	SITE0148	60
SITE0459	15	SITE0175	38	SITE0124	61
SITE0454	16	SITE0169	39	SITE0112	62
SITE0446	17	SITE0168	40	SITE0073	63
SITE0438	18	SITE0167	41	SITE0015	64
SITE0433	19	SITE0166	42	SITE0206	65
SITE0432	20	SITE0128	43	SITE0056	66
SITE0428	21	SITE0103	44	SITE1092	67
SITE0425	22	SITE0091	45	SITE0235	68
SITE0424	23	SITE0082	46	SITE0052	69

Table B-5. Corresponding CEA Site ID to the Ordered Number Sorted by the Frequency of Waveshape Faults in Figure 3-23

CEA Site ID	Number	CEA Site ID	Number	CEA Site ID	Number
SITE1086	1	SITE0213	24	SITE0424	47
SITE1080	2	SITE0175	25	SITE0329	48
SITE1042	3	SITE0167	26	SITE0288	49
SITE0605	4	SITE0166	27	SITE0124	50
SITE0600	5	SITE0103	28	SITE0252	51
SITE0541	6	SITE0064	29	SITE0128	52
SITE0539	7	SITE0037	30	SITE0091	53
SITE0535	8	SITE1018	31	SITE1092	54
SITE0479	9	SITE0616	32	SITE0398	55
SITE0478	10	SITE0488	33	SITE0112	56
SITE0459	11	SITE0218	34	SITE0446	57
SITE0438	12	SITE1083	35	SITE0282	58
SITE0437	13	SITE0543	36	SITE0073	59
SITE0433	14	SITE0523	37	SITE0052	60
SITE0428	15	SITE0168	38	SITE0235	61
SITE0425	16	SITE0015	39	SITE0278	62
SITE0423	17	SITE0515	40	SITE0399	63
SITE0411	18	SITE0443	41	SITE0206	64
SITE0285	19	SITE0298	42	SITE0169	65
SITE0281	20	SITE0148	43	SITE0324	66
SITE0272	21	SITE0056	44	SITE0444	67
SITE0271	22	SITE0034	45	SITE0432	68
SITE0234	23	SITE0454	46	SITE0082	69

APPENDIX C: MATLAB PROGRAM

```
%*************************************************************************
```

C.1. Name: Rural sites voltage profile at the service entrance.

Function: Plot the voltage histogram for each rural site; Calculate the percentage of time voltage fell into difference voltage ranges according to the CAN3-C235-83 standard; Get the minimum, maximum and average/expected voltage for each rural site.

Note: Program for rural sites voltage profile at utilization point is similar, changing standard accordingly.

```
%*************************************************************************

close all;
clear all;
V = load('VotageAll.txt');
MinV = []; MaxV = []; ExpV = [];
Normal = []; ExHigh = []; ExLow = []; High = []; Low = []; OutLow = []; OutHigh = [];

Mstart = 32;
Mend = 32;
for m = Mstart:Mend
  x = V( :,(2*m-1) )/100*120;
  hist = sum(V(:,2*m));
  y = V( :,2*m )/hist;

  %%calculate the time percentage of voltage
  outlow = sum(y(1:9));
  exlow = sum(y(10:12));
  low = sum(y(13:20));
  normal = sum(y(21));
  high = sum(y(22:25));
  exhigh = sum(y(26));
  outhigh = sum(y(27:36));

  OutLow = [OutLow; outlow];
  ExLow = [ExLow; exlow];
```

```
Low = [Low; low];
Normal = [Normal; normal];
High = [High; high];
ExHigh = [ExHigh; exhigh];
OutHigh = [OutHigh; outhigh];

%%get the min, max & expected value of voltage.
expv = sum(x.*y);
for r = 1: size(y,1)
  if y(r)== 0
    r = r+1;
    Flag = 0;
  elseif Flag == 0
    Flag =1;
    minRow = r;
  end
end
minv = x(minRow);
  for r = size(y,1):-1:1
  if y(r)== 0
    r = r-1;
    Flag = 0;
  elseif Flag == 0
    maxRow = r;
    Flag = 1;
  end
end
maxv = x(maxRow);
MinV = [MinV; minv];
MaxV = [MaxV; maxv];
ExpV = [ExpV; expv];


%% plot the bar chart of voltage histogram
figure(m);
bar(x,y);
%set(gca,'XGrid','on','YGrid','on');
set(gca,'XGrid','on','YGrid','on');
set(gca, 'FontWeight', 'bold');
xlabel('VOLTAGE (V)');
ylabel('PERCENTAGE OF TIME');
axis ([95 135 0 0.50]);
% axis ([95 135 0 0.60]);
text(110.3,0.41,'Normal Operating Range', 'FontSize', 10,'FontWeight', 'bold');
text(110, 0.38, '\leftarrow','FontWeight', 'bold');
text(125,0.38,'\rightarrow', 'HorizontalAlignment', 'right','FontWeight', 'bold');
```

```
text(110,0.46,'Extreme Operating Range', 'FontSize', 10,'FontWeight', 'bold');
text(106,0.46,'\leftarrow ','FontWeight', 'bold');
text(127,0.46,'\rightarrow', 'HorizontalAlignment', 'right','FontWeight', 'bold');

text(97,0.36,'Extreme ', 'HorizontalAlignment', 'left','FontSize', 10,'FontWeight', 'bold');
 text(97,0.335,'Undervoltage', 'HorizontalAlignment', 'left','FontSize', 10,'FontWeight',
'bold');
text(97,0.310,'Range', 'HorizontalAlignment', 'left','FontSize', 10,'FontWeight', 'bold');
text(104.9,0.36,'\rightarrow' ,'FontWeight', 'bold');

text(127.9,0.36,'Extreme', 'FontSize', 10,'FontWeight', 'bold');
text(127.9,0.335,'Overvoltage', 'FontSize', 10,'FontWeight', 'bold');
text(127.9,0.31,'Range', 'FontSize', 10,'FontWeight', 'bold');
text(128.2,0.36,'\leftarrow', 'HorizontalAlignment', 'right','FontWeight', 'bold');
title('SITE ');
set(gca,'XTick',[95 100 105 106 110 115 120 125 127 130 135])

set(gca,'YTickLabel',{'0';'0.05';'0.10';'0.15';'0.20';'0.25';'0.30';'0.35';'0.40';'0.45';'0.50'},'F
ontSize', 8)
 %
set(gca,'YTickLabel',{'0';'0.05';'0.10';'0.15';'0.20';'0.25';'0.30';'0.35';'0.40';'0.45';'0.50';'0.5
5';'0.60'},'FontSize', 8)

 set(gca,'XTickLabel',{'95';'100';'105';'    106';'110';'115';'120';'125';'127';'130';'135'})

 end  %%end of m circulation

%%Write the values to .txt files
fid = fopen('VoltStat.txt', 'w');
for m = Mstart:Mend
  fprintf(fid,'%8.2f %8.2f %9.3f %12.8f %12.8f %12.8f %12.8f %12.8f %12.8f %12.8f
\n',MinV(m), MaxV(m), ExpV(m), OutLow(m), ExLow(m),
Low(m),Normal(m),High(m),ExHigh(m), OutHigh(m) );
end
fclose(fid)


%**************************************************************************
```

C.2. Name: Occurrence frequency statistics

Function: If disturbances have the same magnitude and same duration, sum there occurrence frequency up and only output the magnitude, duration and total frequency.

```
%**************************************************************************
```

```
close all;
clear all;

Data = load('surge0511.txt');
%Data = load('sag0511.txt');
%Data = load('swell0511.txt');


Len = size(Data,1);

%Define the constant
Duration = 1;
Magnitude = 2;
Frequency = 3;

Data(:,2) = Data(:,2)/100;

Temp = Data(1,:);
T = Data(1,:);
Tsame = [];
for rowIndex = 2:Len
  if Data(rowIndex, Magnitude) == Data((rowIndex-1), Magnitude)
    Temp = [Temp; Data(rowIndex, :)];
  else
        N = size(Temp,1);
%*************************************************************************
        if N >= 2
                Temp_ordered = sortrows(Temp,1);
                Tsame = Temp_ordered(1,:);

                                for rowIndex_temp = 2:N
                        %delete the last row of T to avoid duplication

                                        if
Temp_ordered(rowIndex_temp,Duration)==Temp_ordered((rowIndex_temp-
1),Duration)
                                                Tsame = [Tsame ; Temp_ordered(rowIndex_temp,
:)];
                else
                M = size(Tsame,1);
                if M>=2
                T = T( 1:(size(T,1)-1),: );
                Freq = 0;
                for rowIndex_same=1:M
                Freq = Freq+Tsame(rowIndex_same,Frequency);
                %Freq = Freq+1;
```

```
            end
                    Tsame = [Tsame(1,1:2),Freq];
            T = [T; Tsame];
            Tsame = Temp_ordered(rowIndex_temp,:);
            %remember to include the last one, which mag is not the same as Tsame.
            Tlast = Temp_ordered(rowIndex_temp,:);
            T=[T;Tlast];
            end
            if M == 1
              T = T( 1:(size(T,1)-1),: );
                                    Tsame = Temp_ordered(rowIndex_temp,:);
          Tcur = Temp_ordered(rowIndex_temp,:);
          %T=[T;Tcur];
          T= [T; Temp_ordered((rowIndex_temp-1),:); Tcur];
            end
      end
  end

end

%aviod the two identical case
    M = size(Tsame,1);
 if M>=2
    T = T( 1:(size(T,1)-1),: );
    Freq = 0;
    for rowIndex_same=1:M
      Freq = Freq+Tsame(rowIndex_same,Frequency);
      %Freq = Freq+1;
    end
    Tsame = [Tsame(1,1:2),Freq];
    T = [T; Tsame];
    Tsame = Temp_ordered(rowIndex_temp,:);
    %remember to include the last one, which mag is not the same as Tsame.
    %Tlast = Temp_ordered(rowIndex_temp,:);
    %T=[T;Tlast];
  end
%end


%*************************************************************************
Temp = Data(rowIndex, :);
T = [T;Temp];
end

end  %% end of 'for'
```

```
%In case the data ends with some data with the same magnitude.
      N = size(Temp,1);

%*************************************************************************
      if N >= 2
            Temp_ordered = sortrows(Temp,1);
            Tsame = Temp_ordered(1,:);

                        for rowIndex_temp = 2:N
                  %delete the last row of T to avoid duplication

                              if
Temp_ordered(rowIndex_temp,Duration)==Temp_ordered((rowIndex_temp-
1),Duration)
                                    Tsame = [Tsame; Temp_ordered(rowIndex_temp,
:)];
      else
        M = size(Tsame,1);
        if M>=2
          T = T( 1:(size(T,1)-1),: );
          Freq = 0;
          for rowIndex_same=1:M
            Freq = Freq+Tsame(rowIndex_same,Frequency);
            %Freq = Freq+1;
          end
              Tsame = [Tsame(1,1:2),Freq];
          T = [T; Tsame];
          Tsame = Temp_ordered(rowIndex_temp,:);
          %remember to include the last one, which mag is not the same as Tsame.
          Tlast = Temp_ordered(rowIndex_temp,:);
          T=[T;Tlast];
        end
        if M == 1
              T = T( 1:(size(T,1)-1),: );
                                    Tsame =
Temp_ordered(rowIndex_temp,:);
          Tcur = Temp_ordered(rowIndex_temp,:);
          %T=[T;Tcur];
          T= [T; Temp_ordered((rowIndex_temp-1),:); Tcur];
        end
      end
    end
  end

  %aviod the two identical case
```

```
  M = size(Tsame,1);
  if M>=2
       T = T( 1:(size(T,1)-1),: );
       Freq = 0;
       for rowIndex_same=1:M
         Freq = Freq+Tsame(rowIndex_same,Frequency);
         %Freq = Freq+1;
       end
       Tsame = [Tsame(1,1:2),Freq];
       T = [T; Tsame];
       Tsame = Temp_ordered(rowIndex_temp,:);
       %remember to include the last one, which mag is not the same as Tsame.
       %Tlast = Temp_ordered(rowIndex_temp,:);
       %T=[T;Tlast];
   end

%*************************************************************************
 % output the data
 %f1= fopen('FreqStatSwell.txt', 'w');
 %f1= fopen('FreqStatSag.txt', 'w');
 f1= fopen('FreqStatSurge.txt', 'w');
       for rowData = 1:size(T,1)
    fprintf(f1,'%12.8f  %12.8f %12.8f\n',T(rowData,:));
 end
 fclose(f1);

%*************************************************************************
```

C.3. Name: Voltage sags' contour lines

Function: Grid the power quality envelope, sum all the voltage sags fell in each grid, average to per site, and link grids with same events exploration per month. Use different color to distinguish the contours. Plot the ITI Curve onto it.

Note: The contour program for voltage swells is the same as voltage sags'. The program for voltage surges has different duration step 1 μs.

```
%*************************************************************************

close all;
clear all;

%Define the constant
```

```
Duration = 1;
Magnitude = 2;
Frequency = 3;

%Define the constant
stepD = 1.0e-1;
stepM = 0.01;

Data = load('FreqStatSag.txt');
Len = size(Data,1);

M = max(Data(:,Magnitude)):-stepM:min(Data(:,Magnitude));
D = min(Data(:,Duration)):stepD:max(Data(:,Duration));
%M = [ 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1, 0 ];
%D = [0,0.2,0.4,0.6,0.8,1,2,3,10];

LenD = length(D);
LenM = length(M);

%%*************************************************************************
%%*****************************************************************
%% divided by duration.
TempD = cell(1,(LenD-1));
for rowIndex = 1: Len
  curDur = Data(rowIndex, Duration);
  for IndexD = 1:(LenD-1)
       if curDur >= D(IndexD) & curDur < D(IndexD+1)
      TempD{1,IndexD} = [TempD{1,IndexD};Data(rowIndex,:)];
    end
  end
end

%%*************************************************************************
%%*************************************************************************
%% sorted by magnitude.
TempDsort = cell(1,(LenD-1));
TempMD = cell(1,(LenD-1));
for IndexD = 1: LenD-1
  curMat = TempD{1,IndexD};
  curMatSort = [];
  if size(curMat,1)>1
    [Y,I] = sort(curMat);
    for IndexTemp = 1:size(I,1)
      curMatSort(IndexTemp,:) = curMat(I(IndexTemp, Magnitude),:);
    end
  else  %% in case the curMat has demision 1, the I is the row order.
```

```
    curMatSort = curMat;
  end
  TempDsort{1,IndexD} = curMatSort;
  %%Grid by Magnitude of TempDsort
  TempM = cell((LenM-1),1);
  for IndexMD = 1:size(curMatSort,1)
    curMag = curMatSort(IndexMD, Magnitude);
    for IndexM = 1:(LenM-1)
                if curMag <= M(IndexM) & curMag > M(IndexM+1)
          TempM{IndexM,1} = [TempM{IndexM,1};curMatSort(IndexMD, :)];
        end
         end
  end
  TempMD{1,IndexD} = TempM;
end

%%*************************************************************************
%%*************************************************************************
%% Average the grided data.
DataGrid = [];
FreqAvgMat = zeros(LenM-1, LenD-1);
FreqMat = zeros(LenM-1, LenD-1);
for IndexD = 1: LenD-1
  curMatD = TempMD{1,IndexD};
  for IndexM = 1:LenM-1
    curMatMD = curMatD{IndexM,1};
                if ~isempty(curMatMD)
        if size(curMatMD,1) >1
        curMDsum = sum(curMatMD);
        FreqSum = curMDsum(1,Frequency);
        FreqAvg = FreqSum/69;
        curMDavg = mean(curMatMD);
        curMDgrid = [curMDavg(Duration),curMDavg(Magnitude),FreqSum];
        DataGrid = [DataGrid;curMDgrid];

        FreqAvgMat(IndexM, IndexD) = FreqAvg;
        FreqMat(IndexM, IndexD) = FreqSum;

        elseif ~isempty(curMatMD)
        curMDgrid =
[curMatMD(Duration),curMatMD(Magnitude),curMatMD(Frequency)];
        DataGrid = [DataGrid;curMDgrid];
        FreqAvgMat(IndexM, IndexD) = curMatMD(Frequency)/69;
        FreqMat(IndexM, IndexD) = curMatMD(Frequency);
      end
    end
```

```
  end
end

%%*************************************************************************
%%*************************************************************************
%% output the data

RowFreqMat = size(FreqMat,1);
ColmFreqMat = size(FreqMat,2);
ContourMat = [];

for rowIndex = 1:RowFreqMat
   for colmIndex = 1:ColmFreqMat
      curFreqMat = FreqMat(rowIndex:RowFreqMat, colmIndex:ColmFreqMat);
      ContourMat(rowIndex, colmIndex) = sum(sum(curFreqMat));
   end
end

fl = fopen('GridSag.txt','w');
for IndexRow = 1:size(FreqMat,1)
  for IndexColumn = 1:size(FreqMat,2)
    fprintf(fl,'%12.6f',FreqMat(IndexRow,IndexColumn));
  end
  fprintf(fl,'\n');
end

fprintf(fl,'\n');
fprintf(fl,'\n');

for IndexRow = 1:size(ContourMat,1)
  for IndexColumn = 1:size(ContourMat,2)
    %fprintf(fl,'%12.6f',ContourMat(IndexRow,IndexColumn));
    fprintf(fl,'%12.6f',ContourMat(IndexRow,IndexColumn)/69);
  end
  fprintf(fl,'\n');
end

fclose(fl);

%%*************************************************************************
%%*************************************************************************

DataGrid_01 = [];DataGrid_05 = [];DataGrid_1 = [];DataGrid_5 = [];DataGrid_10 = [];
ContourAvgMat = ContourMat/69;
for IndxColumn = 1: size(ContourAvgMat,2)
```

```
 for IndxRow = size(ContourAvgMat,1):-1:2
    CurCumuFreq = ContourAvgMat(IndxRow, IndxColumn);
    BigCumuFreq = ContourAvgMat((IndxRow-1), IndxColumn);

     if CurCumuFreq <0.1 & (BigCumuFreq >= 0.1 & BigCumuFreq < 0.5)
        DataGrid_01 = [DataGrid_01;IndxRow-1, IndxColumn];
     elseif CurCumuFreq <0.5 & (BigCumuFreq >= 0.5 & BigCumuFreq < 1)
        DataGrid_05 = [DataGrid_05;IndxRow-1, IndxColumn];
     elseif CurCumuFreq <1 & (BigCumuFreq >= 1 & BigCumuFreq < 5)
        DataGrid_1 = [DataGrid_1;IndxRow-1, IndxColumn];
     elseif CurCumuFreq <5 & (BigCumuFreq >= 5 & BigCumuFreq < 10)
        DataGrid_5 = [DataGrid_5;IndxRow-1, IndxColumn];
     elseif CurCumuFreq <10 & (BigCumuFreq >= 10)
        DataGrid_10 = [DataGrid_10;IndxRow-1, IndxColumn];
     end

  end
end

%%to make the countour lines continuing
Add_01 = []; Add_05 = []; Add_1 = []; Add_5 = []; Add_10 = [];

for IndexR = 1:(size(DataGrid_01, 1)-1)
   curMag = DataGrid_01(IndexR, 1);
   curDur = DataGrid_01(IndexR, 2);
   nextMag = DataGrid_01( (IndexR+1), 1 );
   Defn = curMag-nextMag;
   AddGrid_01 = [ ];
   if Defn>=1
      DefnMat = ContourAvgMat ( nextMag:curMag, curDur );
      DefnMag = find(DefnMat>0.1& DefnMat<0.5);
      curMagExp = ContourAvgMat ( (nextMag+DefnMag(1)-1), curDur );
      Defn = curMag- (nextMag+DefnMag(1)-1);
         for IndexC = Defn:-1:1
            AddGrid_01=[ AddGrid_01; curMag-IndexC,curDur ];
         end
      DataGrid_01 = [DataGrid_01;AddGrid_01];
   end
   Add_01 = [Add_01; AddGrid_01];
end

 for IndexR = 1:(size(DataGrid_05, 1)-1)
    curMag = DataGrid_05(IndexR, 1);
    curDur = DataGrid_05(IndexR, 2);
    nextMag = DataGrid_05( (IndexR+1), 1 );
    Defn = curMag-nextMag;
```

```
    AddGrid_05 = [ ];
    if Defn>=1
       DefnMat = ContourAvgMat ( nextMag:curMag, curDur );
       DefnMag = find(DefnMat>0.5& DefnMat<1);
       curMagExp = ContourAvgMat ( (nextMag+DefnMag(1)-1), curDur );
       Defn = curMag- (nextMag+DefnMag(1)-1);
          for IndexC = Defn:-1:1
             AddGrid_05=[ AddGrid_05; curMag-IndexC,curDur ];
          end
       DataGrid_05 = [DataGrid_05;AddGrid_05];
    end
      Add_05 = [Add_05; AddGrid_05];
end

for IndexR = 1:(size(DataGrid_1, 1)-1)
    curMag = DataGrid_1(IndexR, 1);
    curDur = DataGrid_1(IndexR, 2);
    nextMag = DataGrid_1( (IndexR+1), 1 );
    Defn = curMag-nextMag;
    AddGrid_1 = [ ];
    if Defn>=1
       DefnMat = ContourAvgMat ( nextMag:curMag, curDur );
       DefnMag = find(DefnMat>1& DefnMat<5);
       curMagExp = ContourAvgMat ( (nextMag+DefnMag(1)-1), curDur );
       Defn = curMag- (nextMag+DefnMag(1)-1);
          for IndexC = Defn:-1:1
             AddGrid_1=[ AddGrid_1; curMag-IndexC,curDur ];
          end
       DataGrid_1 = [DataGrid_1;AddGrid_1];
    end
      Add_1 = [Add_1; AddGrid_1];
end

for IndexR = 1:(size(DataGrid_5, 1)-1)
    curMag = DataGrid_5(IndexR, 1);
    curDur = DataGrid_5(IndexR, 2);
    nextMag = DataGrid_5( (IndexR+1), 1 );
    Defn = curMag-nextMag;
    AddGrid_5 = [ ];
    if Defn>=1
       DefnMat = ContourAvgMat ( nextMag:curMag, curDur );
       DefnMag = find(DefnMat>5& DefnMat<10);
       curMagExp = ContourAvgMat ( (nextMag+DefnMag(1)-1), curDur );
       Defn = curMag- (nextMag+DefnMag(1)-1);
          for IndexC = Defn:-1:1
             AddGrid_5=[ AddGrid_5; curMag-IndexC,curDur ];
```

```
        end
      DataGrid_5 = [DataGrid_5;AddGrid_5];
    end
     Add_5 = [Add_5; AddGrid_5];
end

for IndexR = 1:(size(DataGrid_10, 1)-1)
   curMag = DataGrid_10(IndexR, 1);
   curDur = DataGrid_10(IndexR, 2);
   nextMag = DataGrid_10( (IndexR+1), 1 );
   Defn = curMag-nextMag;
   AddGrid_10 = [ ];
   if Defn>=1
      DefnMat = ContourAvgMat ( nextMag:curMag, curDur );
      DefnMag = find(DefnMat>10);
      curMagExp = ContourAvgMat ( (nextMag+DefnMag(1)-1); curDur );
      Defn = curMag- (nextMag+DefnMag(1)-1);
         for IndexC = Defn:-1:1
            AddGrid_10=[ AddGrid_10; curMag-IndexC,curDur ];
         end
      DataGrid_10 = [DataGrid_10;AddGrid_10];
   end
     Add_10 = [Add_10; AddGrid_10];
end


%%**************************************************************************
%% For plotting.
%%**************************************************************************

% sag plot
figure (1);
grid on;
for Index = 1:size(DataGrid_01, 1)
  Dur = D(DataGrid_01(Index,2));
  Mag = M(DataGrid_01(Index,1));
  x =[Dur,  Dur,(Dur+stepD),(Dur+stepD)];
  y = [(Mag-stepM),Mag, Mag, (Mag-stepM)];
  hold on;
  patch(x,y,'r');
end
for Index = 1:size(DataGrid_05, 1)
  Dur = D(DataGrid_05(Index,2));
  Mag = M(DataGrid_05(Index,1));
  x =[Dur, Dur, (Dur+stepD), (Dur+stepD)];
  y = [(Mag-stepM),Mag, Mag, (Mag-stepM)];
```

```
  hold on;
  patch(x,y,'y');
end
for Index = 1:size(DataGrid_1, 1)
 Dur = D(DataGrid_1(Index,2));
  Mag = M(DataGrid_1(Index,1));
  x =[Dur, Dur, (Dur+stepD), (Dur+stepD)];
  y = [(Mag-stepM),Mag, Mag, (Mag-stepM)];
  hold on;
  patch(x,y,'b');
end
for Index = 1:size(DataGrid_5, 1)
  Dur = D(DataGrid_5(Index,2));
  Mag = M(DataGrid_5(Index,1));
  x =[Dur, Dur, (Dur+stepD), (Dur+stepD)];
  y = [(Mag-stepM),Mag, Mag, (Mag-stepM)];
  hold on;
  patch(x,y,'g');
end
for Index = 1:size(DataGrid_10, 1)
   Dur = D(DataGrid_10(Index,2));
  Mag = M(DataGrid_10(Index,1));
  x =[Dur, Dur, (Dur+stepD), (Dur+stepD)];
  y = [(Mag-stepM),Mag, Mag, (Mag-stepM)];
  hold on;
  patch(x,y,'k');
end

xlabel('Duration (s)');
ylabel('Magnitude (% of nominal voltage)');
title('Voltage Sag');
legend('>=0.1', '>=0.5', '>=1', '>=5', '>=10');
axis([0, 10, 0.5, 1 ]);

%%*************************************************************************
%% ITI Curve plot
%%*************************************************************************
upper = [  1.67E-04   500
           1.00E-03  200
           3.00E-03  140
           3.00E-03  120
           2.00E-02  120
           5.00E-01  120
           5.00E-01  110
           1.67E+00 110
           1.00E+01 110
```

```
                ];
upper(:,2) = upper(:,2)/100;

bottom = [ 2.00E-02   0
           2.00E-02  40
           2.00E-02  70
           1.67E-01  70
           5.00E-01  70
           5.00E-01  80
           1.00E+01  80
           1.00E+01  90
            ];
 bottom(:,2) = bottom(:,2)/100;

 stepM = 0.01;
  LW = 4;

if 0 %% for sags, upper limit is not necessary
  for IndexRow = 1:( size(upper, 1)-1 )
    curMag = upper(IndexRow,2);
    curDur = upper(IndexRow, 1);
    nextMag = upper( (IndexRow+1),2 );
    nextDur = upper( (IndexRow+1), 1 );
    if curDur <=1e-2
       stepD = 1e-4;
    elseif  curDur <=1e-1
       stepD = 1e-3;
    elseif curDur <=1e+2
       stepD = 1e-2;
    end

    if curMag == nextMag
        line(curDur:stepD :nextDur, curMag, 'linewidth', LW, 'marker', '.',  'color',
[0,0,0]);
    elseif curDur == nextDur
        line(curDur, curMag:-stepM/10:nextMag, 'linewidth', LW, 'marker', '.',  'color',
[0,0,0]);
     else
        steps = length( curMag:-stepM:nextMag )-1;
        line(curDur:(nextDur-curDur)/steps :nextDur, curMag:-stepM:nextMag,
'linewidth', LW, 'marker', '.',  'color', [0,0,0]);
      end
   end
end%% for sags, upper limit is not necessary

   for IndexRow = 1:( size(bottom, 1)-1 )
```

```
    curMag = bottom(IndexRow,2);
    curDur = bottom(IndexRow, 1);
    nextMag = bottom( (IndexRow+1),2 );
    nextDur = bottom( (IndexRow+1), 1 );

    if curDur <=1e-2
       stepD = 1e-4;
    elseif  curDur <=1e-1
       stepD = 1e-3;
    elseif curDur <=1e+2
       stepD = 1e-2;
    end

    if curMag == nextMag
        line(curDur:stepD :nextDur, curMag, 'linewidth', LW, 'marker',  '.',  'color',
[0,0,0]);
    elseif curDur == nextDur
        line(curDur, curMag:stepM/10:nextMag, 'linewidth', LW, 'marker',  '.',  'color',
[0,0,0]);
     else
        steps = length( curMag:-stepM:nextMag )-1;
        line(curDur:(nextDur-curDur)/steps :nextDur, curMag:stepM:nextMag,
'linewidth', LW, 'marker',   '.',   'color',  [0,0,0]);
      end
   end

%**************************************************************************
```

C.4. Name: Defining the Canadian rural electrical environment.

Function: Grid all the rural disturbances according to their magnitude and duration.

```
%**************************************************************************

close all;
clear all;

%Define the constant
Duration = 1;
Magnitude = 2;
Frequency = 3;
cyc = 1/60;

%Define the constant
M = [11,5, 4,3,2,1.4,1.2, 1.1, 1.06, 0.9, 0.8, 0.7, 0.5, 0.1, 0 ]*100;
```

```
D = [1e-6,0.001*cyc, 0.01*cyc, 0.001, 0.003, 1*cyc, 6*cyc, 10*cyc, 20*cyc,30*cyc,0.5,
1, 2, 10, 6000];
Data = load('data.txt');
Len = size(Data,1);

LenD = length(D);
LenM = length(M);

grid = zeros(LenD,LenM);

%%*************************************************************************
%%*************************************************************************
%% divided by duration.
TempD = cell(1,(LenD-2));
for rowIndex = 1: Len
  curDur = Data(rowIndex, Duration);
  [Y,I05] = find(D==0.5);
  for IndexD = 1:(I05(2)-2)
       if curDur > D(IndexD) & curDur <= D(IndexD+1)
      TempD{1,IndexD} = [TempD{1,IndexD};Data(rowIndex,:)];
    end
  end
  for IndexD = I05(2):(LenD-1)
       if curDur >= D(IndexD) & curDur < D(IndexD+1)
      TempD{1,(IndexD-1)} = [TempD{1,(IndexD-1)};Data(rowIndex,:)];
    end
 end
end

%%*************************************************************************
%%*************************************************************************
%% sorted by magnitude.
TempDsort = cell(1,(LenD-2));
TempMD = cell(1,(LenD-2));
for IndexD = 1: LenD-2
  curMat = TempD{1,IndexD};
  curMatSort = [];
  if size(curMat,1)>1
    [Y,I] = sort(curMat);
    for IndexTemp = 1:size(I,1)
      curMatSort(IndexTemp,:) = curMat(I(IndexTemp, Magnitude),:);
    end
  else  %% in case the curMat has demision 1, the I is the row order.
    curMatSort = curMat;
  end
  TempDsort{1,IndexD} = curMatSort;
```

```
%%Grid by Magnitude of TempDsort
TempM = cell((LenM-2),1);
for IndexMD = 1:size(curMatSort,1)
  curMag = curMatSort(IndexMD, Magnitude);
  [Y,I90] = find(M==90);
  for IndexM = 1:(I90-2)
            if curMag < M(IndexM) & curMag >= M(IndexM+1)
      TempM{IndexM,1} = [TempM{IndexM,1};curMatSort(IndexMD, :)];
     end
      end
  for IndexM = I90:(LenM-1)
            if curMag <= M(IndexM) & curMag > M(IndexM+1)
      TempM{(IndexM-1),1} = [TempM{(IndexM-1),1};curMatSort(IndexMD, :)];
     end
      end
 end
 TempMD{1,IndexD} = TempM;
end

%%*************************************************************************
%%*************************************************************************
%% Average the grided data.
DataGrid = [];
FreqAvgMat = zeros(LenM-2, LenD-2);
FreqMat = zeros(LenM-2, LenD-2);
for IndexD = 1: LenD-2
  curMatD = TempMD{1,IndexD};
  for IndexM = 1:LenM-2
    curMatMD = curMatD{IndexM,1};
            if ~isempty(curMatMD)
      if size(curMatMD,1) >1
      curMDsum = sum(curMatMD);
      FreqSum = curMDsum(1,Frequency);
      FreqAvg = FreqSum/69;
      curMDavg = mean(curMatMD);
      curMDgrid = [curMDavg(Duration),curMDavg(Magnitude),FreqSum];
      DataGrid = [DataGrid;curMDgrid];

      FreqAvgMat(IndexM, IndexD) = FreqAvg;
      FreqMat(IndexM, IndexD) = FreqSum;

      elseif ~isempty(curMatMD)
      curMDgrid =
[curMatMD(Duration),curMatMD(Magnitude),curMatMD(Frequency)];
      DataGrid = [DataGrid;curMDgrid];
      FreqAvgMat(IndexM, IndexD) = curMatMD(Frequency)/69;
```

```
        FreqMat(IndexM, IndexD) = curMatMD(Frequency);
      end
    end
  end
end

%%*************************************************************************
%%*************************************************************************
%% output the data

f1 = fopen('Grid.txt','w');
for IndexRow = 1:size(FreqMat,1)
  for IndexColumn = 1:size(FreqMat,2)
    fprintf(f1,'%12.6f',FreqMat(IndexRow,IndexColumn));
  end
  fprintf(f1,'\n');
end
fclose(f1);
```

APPENDIX D: Digitalized results of other customer types in the CEA Survey

Table D-1 CEA Industrial Power Supply Low RMS Disturbance per Month

Mag. vs Dur.	1 ~ 6 cy.	6~10 cy.	10~20 cy.	20~30 cy.	0.5 ~ 1 sec.	1 ~ 2 sec.	2 ~10 sec.	>10 sec.	Average No. of Events
> 110%	0.25	0.17	0.43	0.33	0.80	0.70	0.00	0	2.68
106% ~ 110%	0.00	0.00	0.00	0.02	0.40	1.70	13.20	0	15.32
80% ~ 90%	0.08	0.30	10.35	8.40	9.15	12.20	12.10	0	52.58
70% ~ 80%	2.22	1.41	3.08	2.73	3.95	5.20	2.30	0	20.90
50% ~ 70%	0.42	0.51	0.40	0.00	0.00	0.00	1.90	0	3.22
10% ~ 50%	0.00	0.00	0.00	0.00	0.00	0.00	2.20	0	2.20
0% ~ 10%	0.00	0.00	0.00	0.00	0.00	0.00	1.30	0	1.30
Average No. of Events	2.97	2.38	14.27	11.48	14.30	19.80	33.00	0.00	98.21

Table D-2 CEA Commercial Power Supply Low RMS Disturbance per Month

Mag. vs Dur.	1 ~ 6 cy.	6~10 cy.	10~20 cy.	20~30 cy.	0.5 ~ 1 sec.	1 ~ 2 sec.	2 ~10 sec.	>10 sec.	Average No. of Events
> 110%	0.76	0.58	0.92	0.77	1.60	2.70	2.60	0	9.92
106% ~ 110%	0.00	0.07	0.53	0.83	3.20	7.10	12.00	0	23.73
80% ~ 90%	0.71	1.91	6.52	3.05	3.50	0.30	2.50	0	18.48
70% ~ 80%	2.31	0.63	1.25	1.03	0.00	0.00	2.10	0	7.32
50% ~ 70%	0.60	0.35	0.05	0.00	0.00	0.00	2.20	0	3.20
10% ~ 50%	0.02	0.00	0.00	0.00	0.00	0.00	2.60	0	2.62
0% ~ 10%	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0	1.00
Average No. of Events	4.39	3.53	9.27	5.68	8.30	10.10	25.00	0.00	66.28

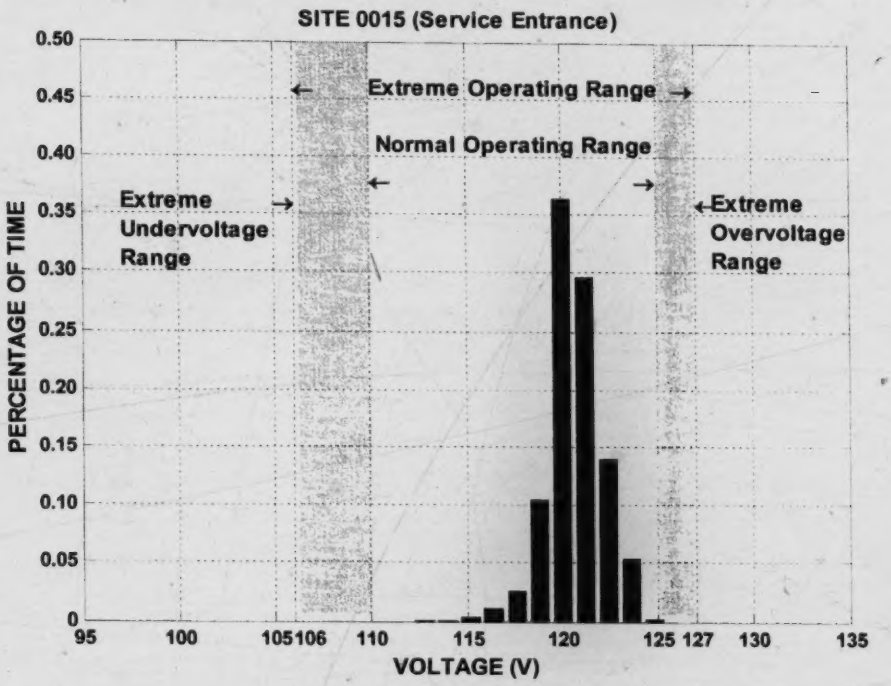
Table D-3 CEA Residential Power Supply Low RMS Disturbance per Month

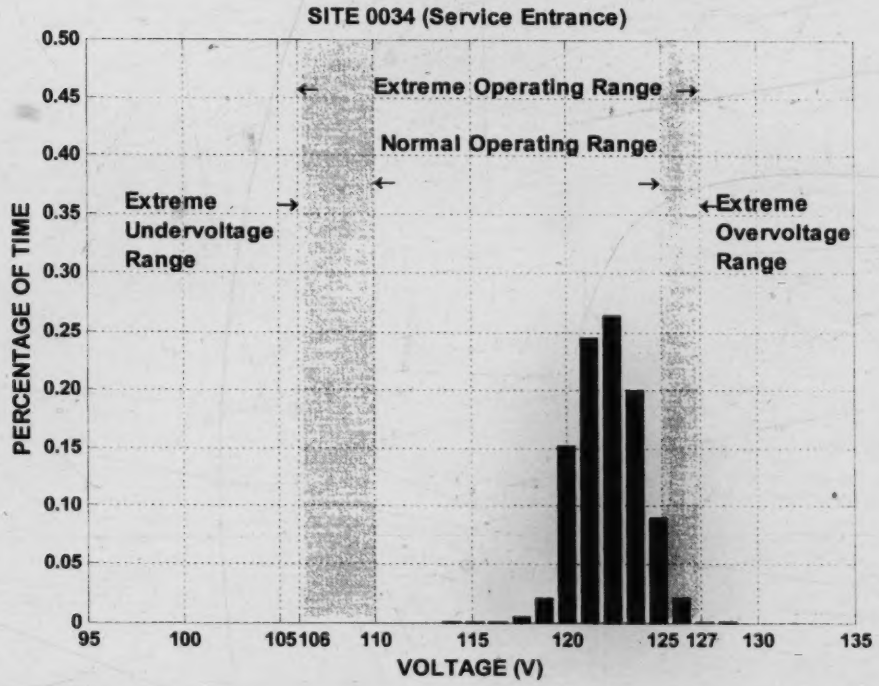
Mag. vs Dur.	1 ~ 6 cy.	6~10 cy.	10~20 cy.	20~30 cy.	0.5 ~ 1 sec.	1 ~ 2 sec.	2 ~10 sec.	>10 sec.	Average No. of Events
> 110%	0.00	0.00	0.75	0.95	3.35	4.40	3.00	0	12.45
106% ~ 110%	0.00	0.00	0.00	0.00	0.05	2.00	9.20	0	11.25
80% ~ 90%	1.00	0.57	2.57	2.72	7.60	11.20	3.10	0	28.75
70% ~ 80%	1.22	1.01	1.35	1.00	1.90	0.00	1.20	0	7.68
50% ~ 70%	0.65	0.50	0.63	0.00	0.00	0.00	1.10	0	2.88
10% ~ 50%	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0	1.00
0% ~ 10%	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0	0.90
Average No. of Events	2.87	2.08	5.30	4.67	12.90	17.60	19.50	0.00	64.91

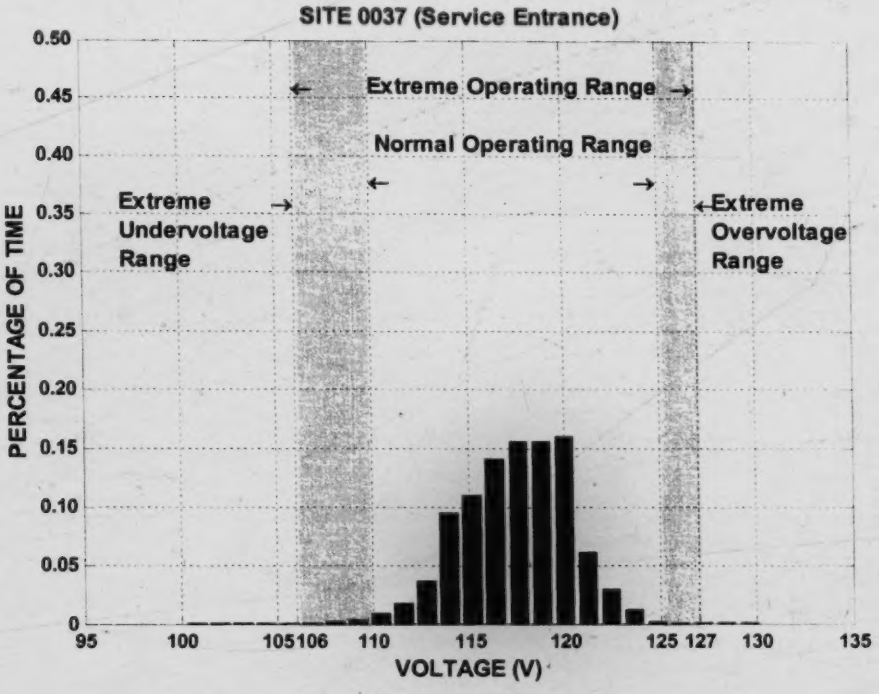
Table D-4 CEA Primary Power Supply Low RMS Disturbance per Month

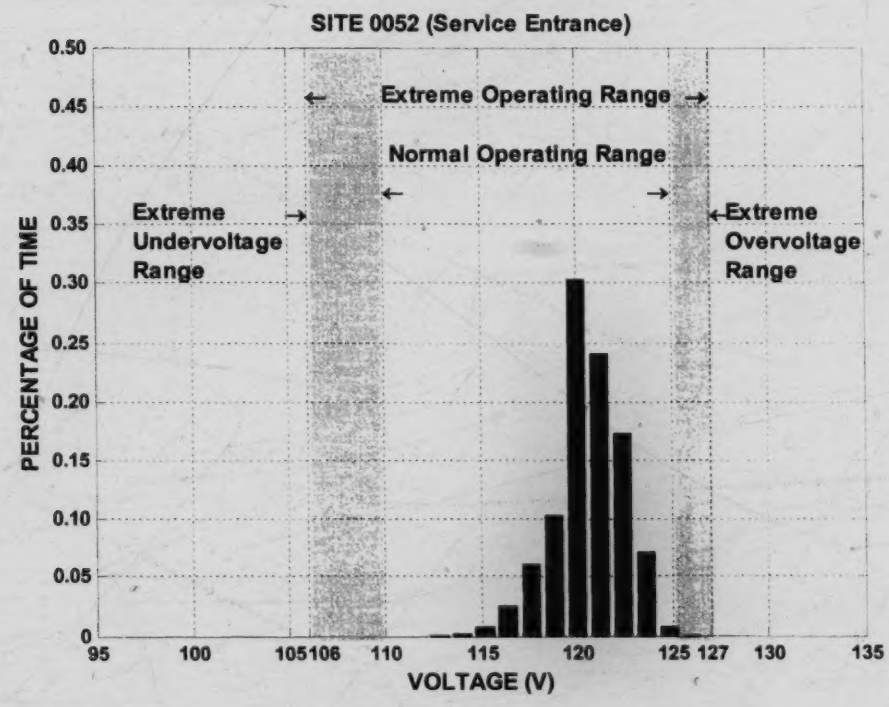
Mag. vs Dur.	1 ~ 6 cy.	6~10 cy.	10~20 cy.	20~30 cy.	0.5 ~ 1 sec.	1 ~ 2 sec.	2 ~10 sec.	>10 sec.	Average No. of Events
> 110%	0.00	0.10	0.42	0.35	0.70	1.10	0.60	0	3.27
106% ~ 110%	0.00	0.00	0.00	0.02	0.15	1.20	9.60	0	10.97
80% ~ 90%	0.00	1.15	4.48	1.35	2.15	1.00	2.50	0	12.63
70% ~ 80%	0.62	0.50	0.17	0.00	1.30	2.00	0.10	0	4.68
50% ~ 70%	0.00	0.00	0.05	0.42	0.70	0.00	0.00	0	1.17
10% ~ 50%	0.00	0.00	0.45	0.03	0.00	0.00	0.00	0	0.48
0% ~ 10%	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0	0.18
Average No. of Events	0.62	1.75	5.57	2.35	5.00	5.30	12.80	0.00	33.38

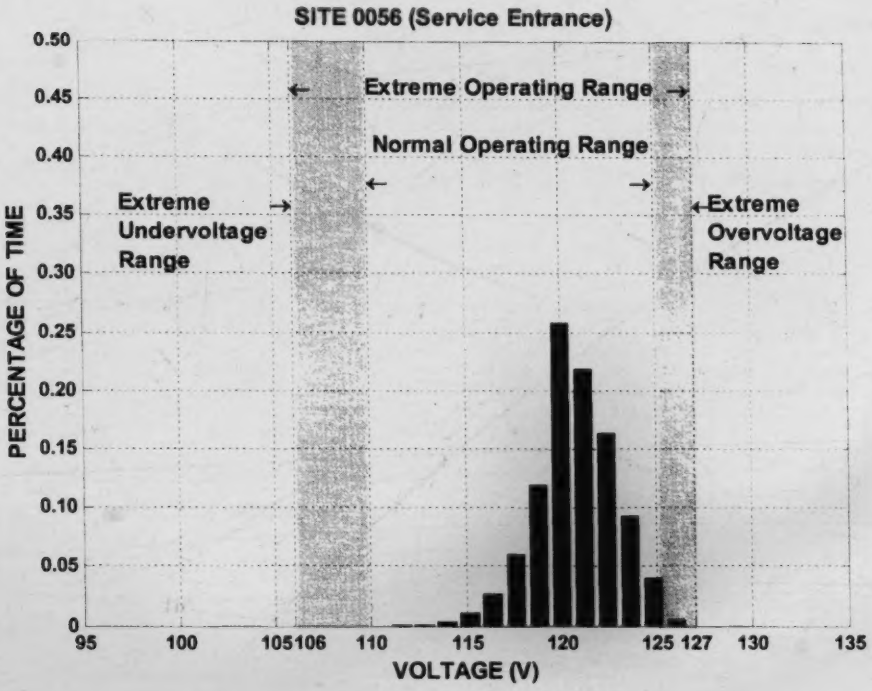
APPENDIX E: Sampled rural site voltage histograms

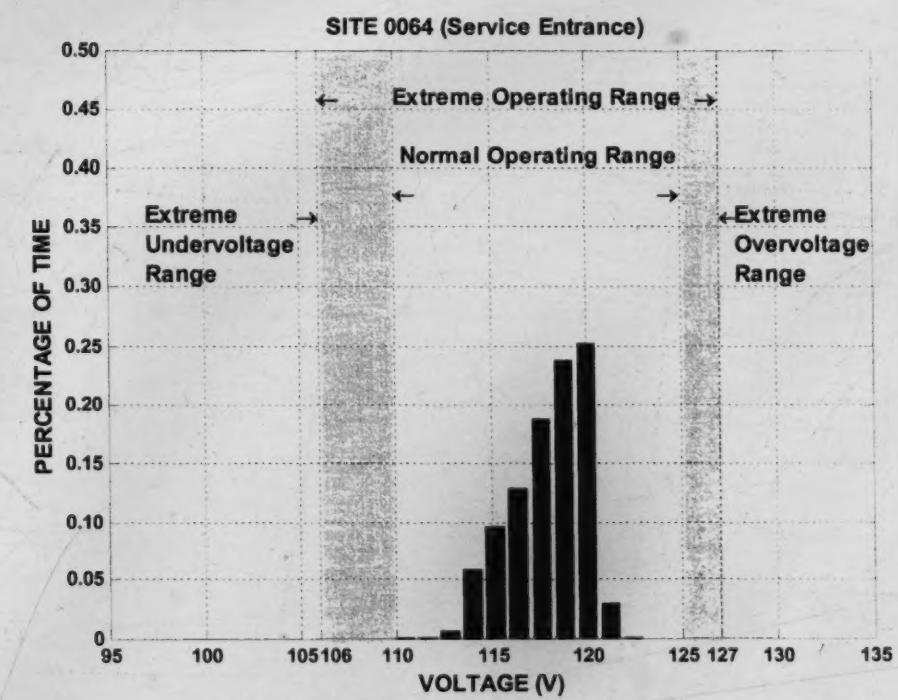


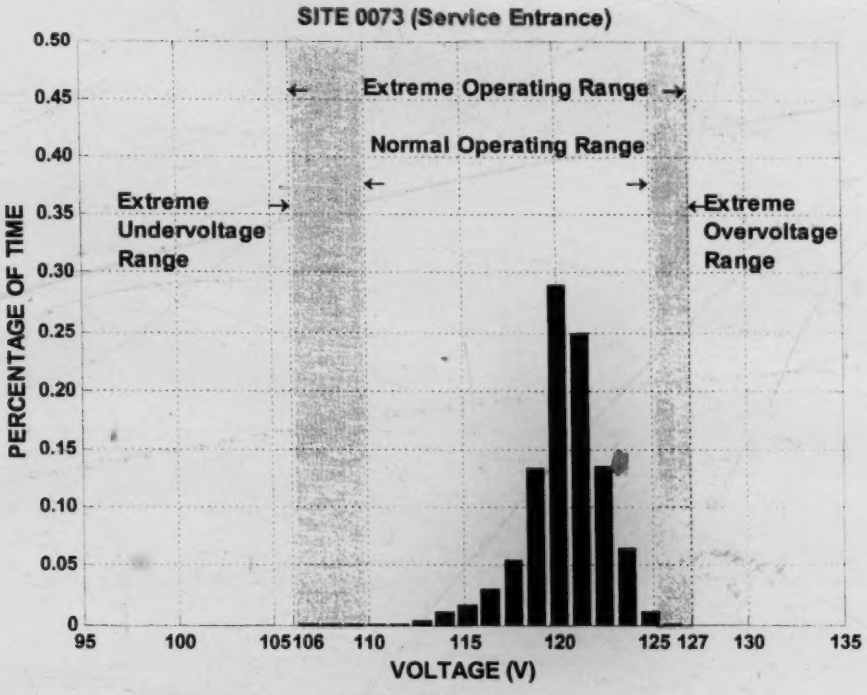


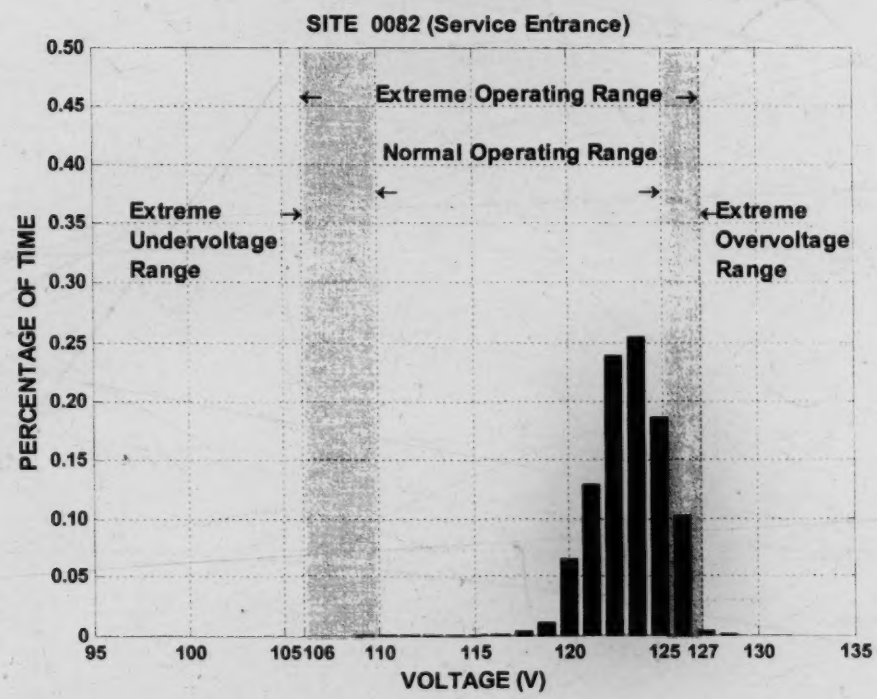

SITE 0037 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

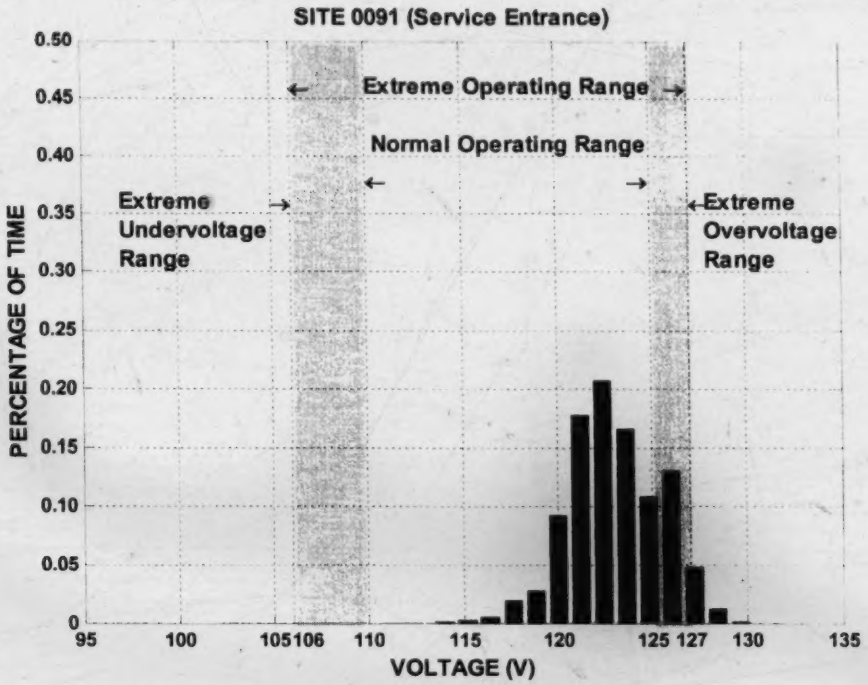

SITE 0052 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

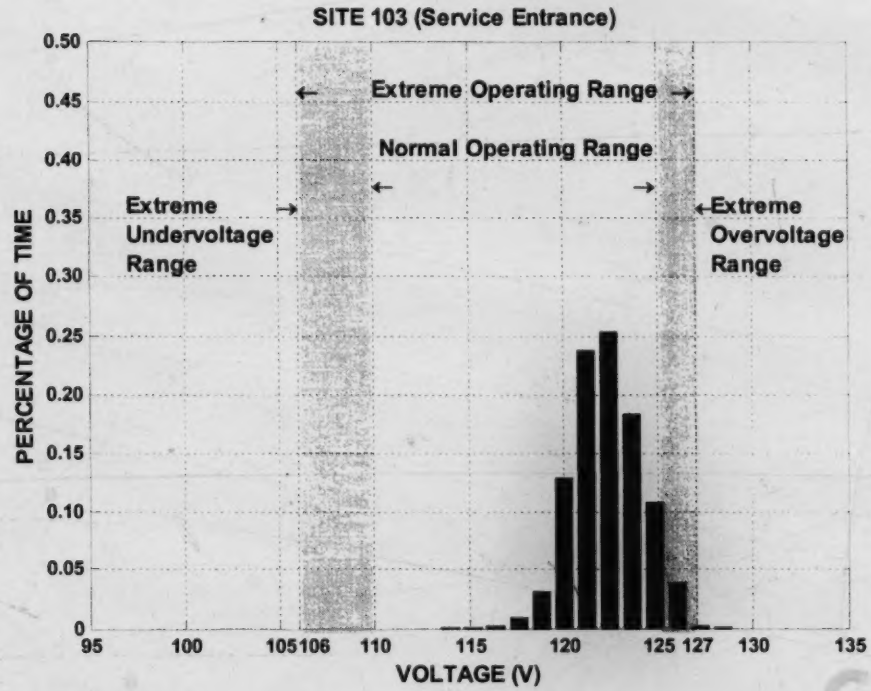

SITE 0056 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

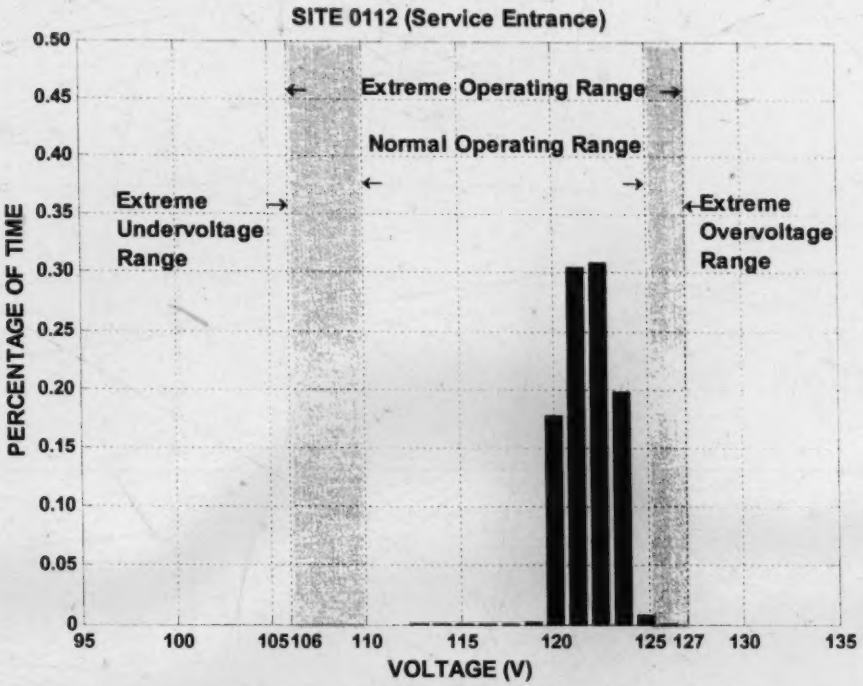

SITE 0064 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

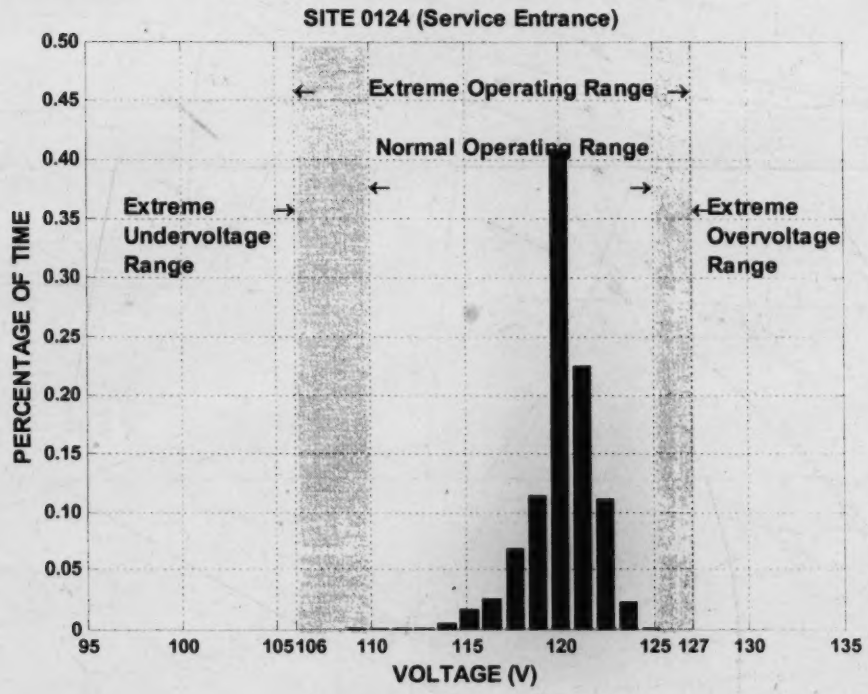

SITE 0073 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

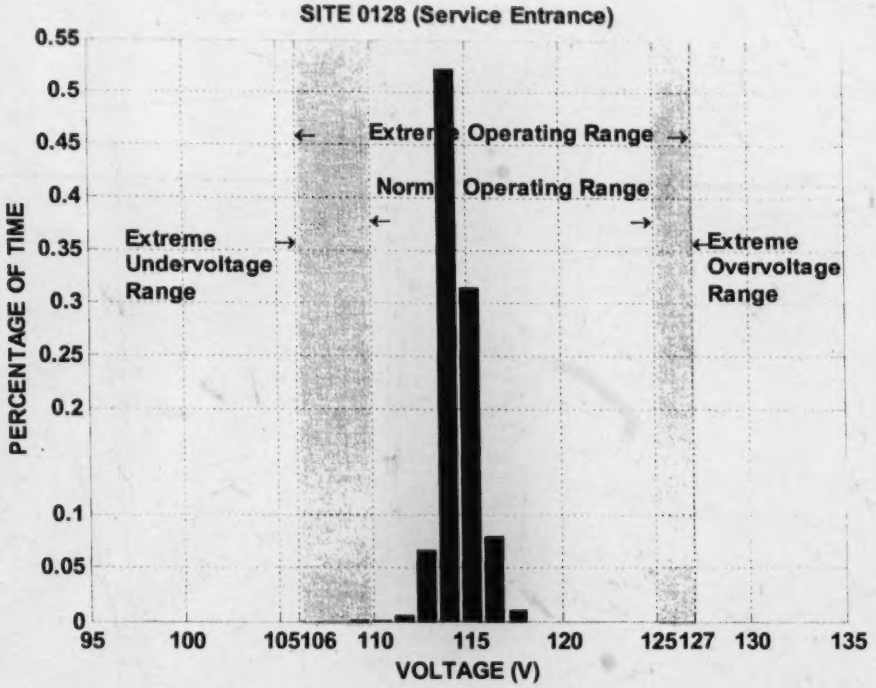

SITE 0082 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

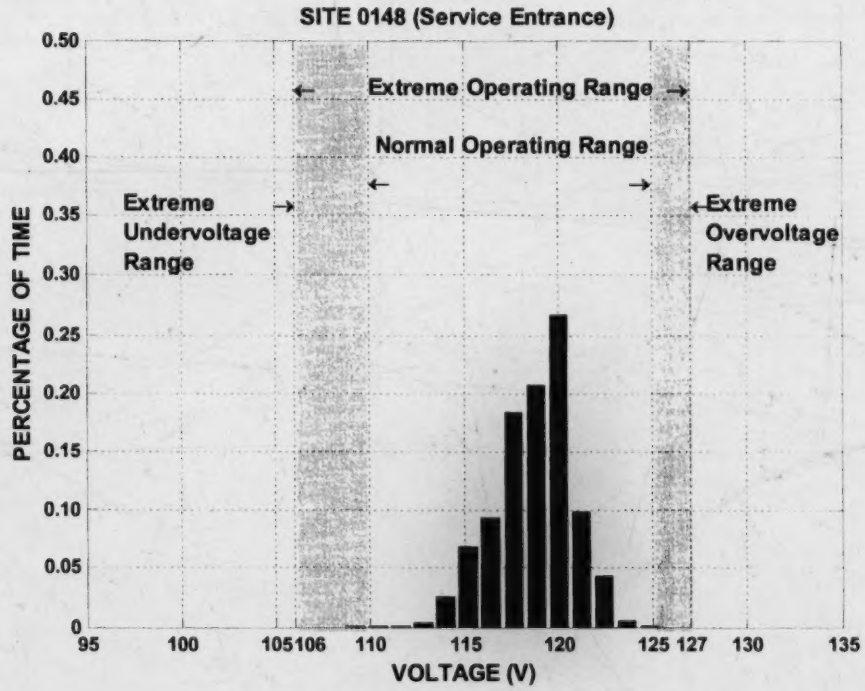

SITE 0091 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

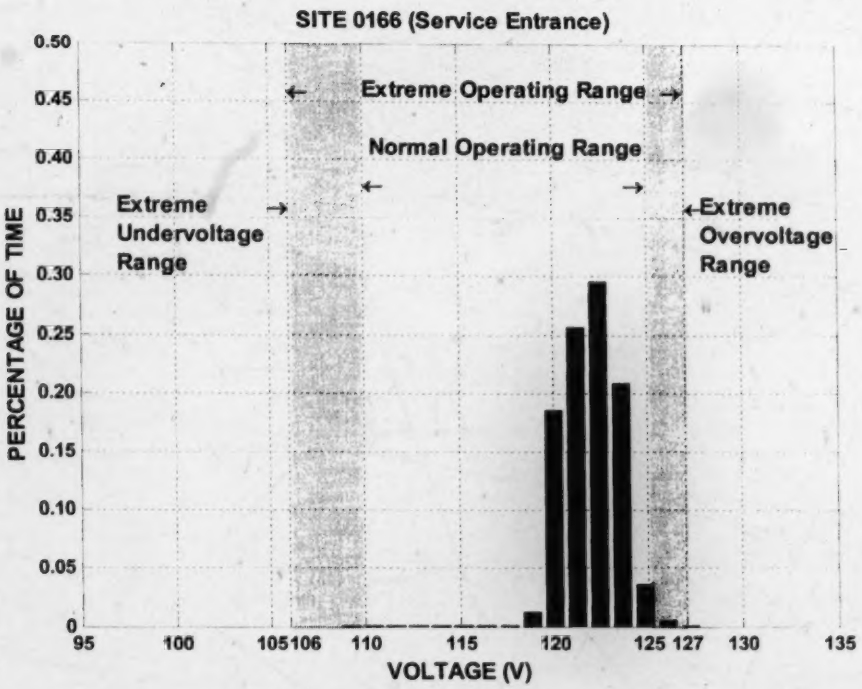

SITE 103 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

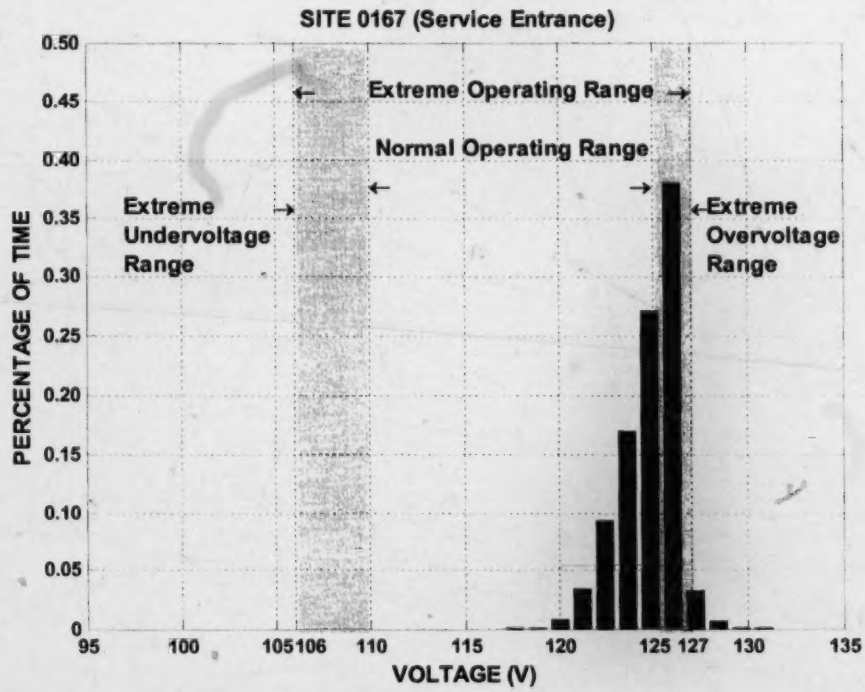

SITE 0112 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135
VOLTAGE (V)

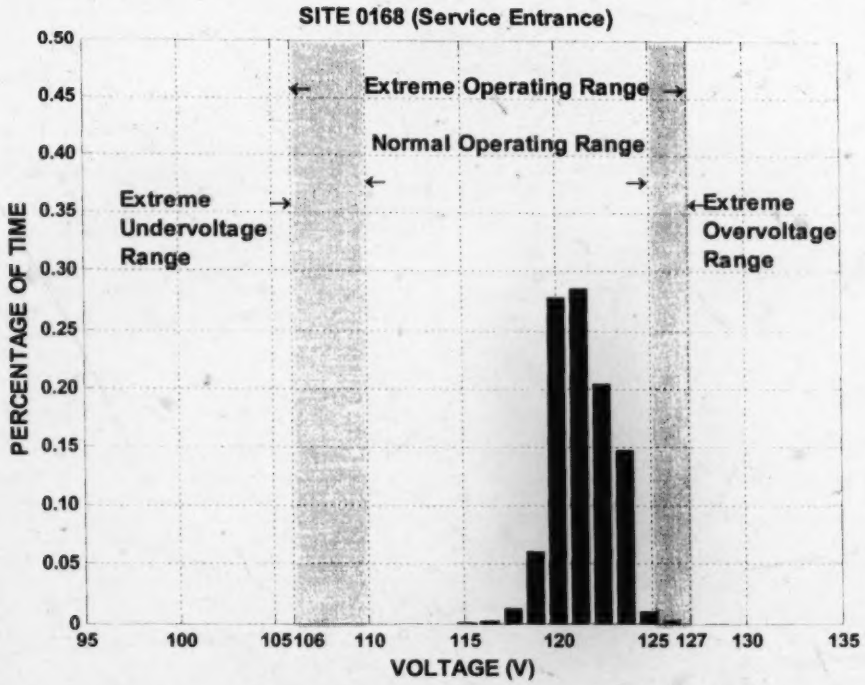

SITE 0124 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135
VOLTAGE (V)

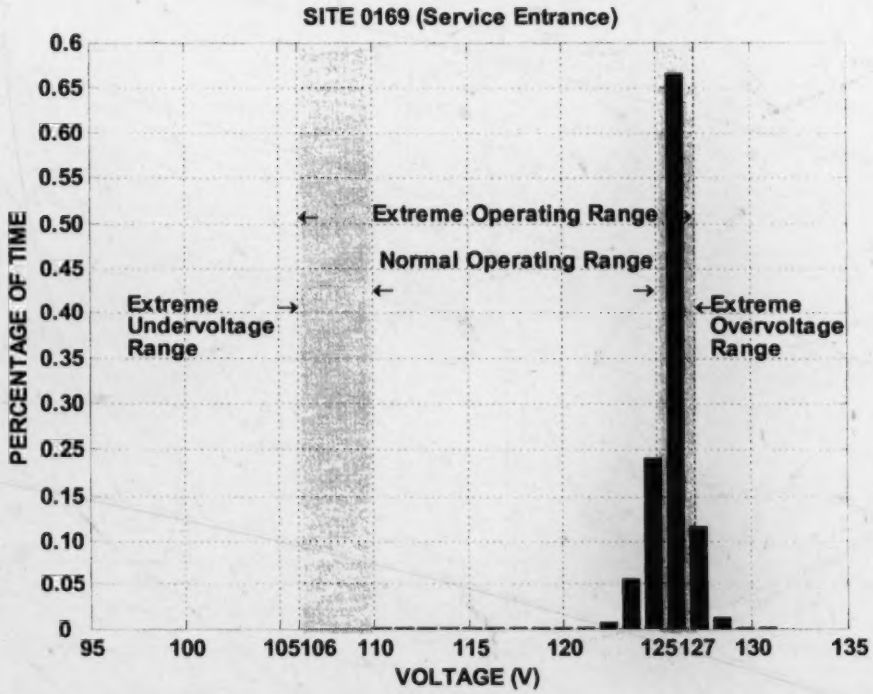

SITE 0128 (Service Entrance)
PERCENTAGE OF TIME
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.1
0.05
0
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
95
100
105
106
110
115
120
125
127
130
135
VOLTAGE (V)

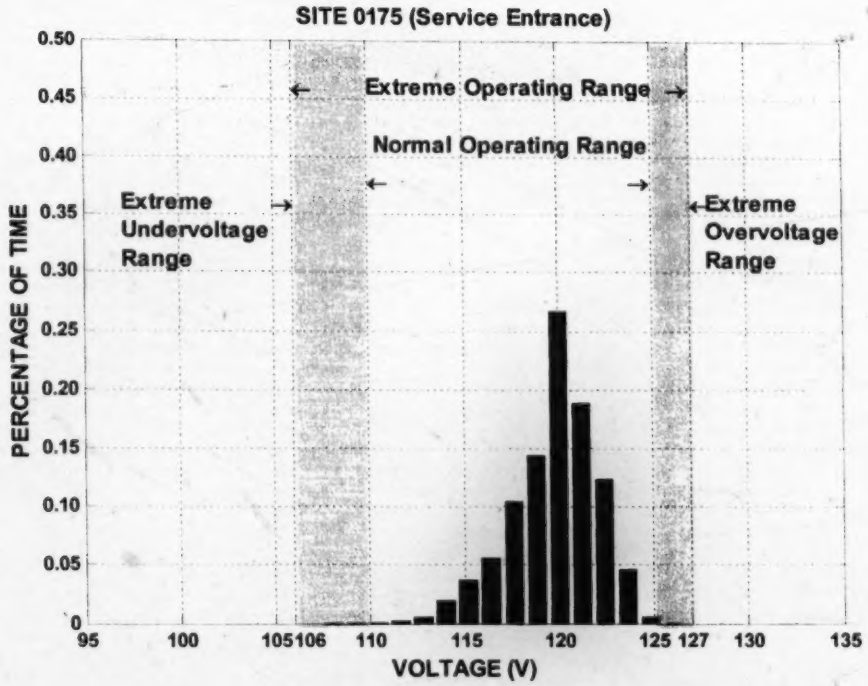

SITE 0148 (Service Entrance)
PERCENTAGE OF TIME
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
95
100
105
106
110
115
120
125
127
130
135
VOLTAGE (V)

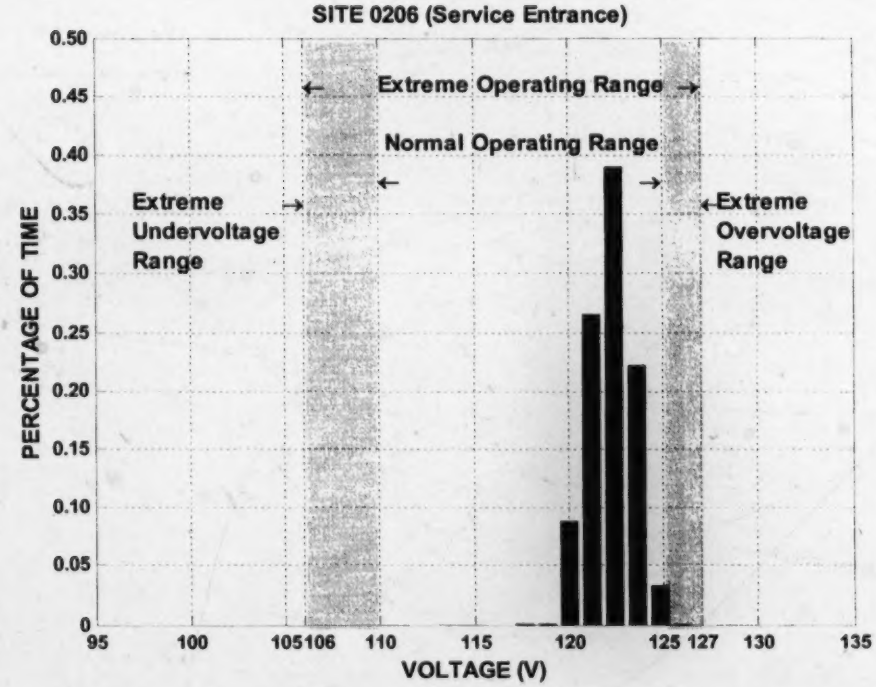

SITE 0166 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

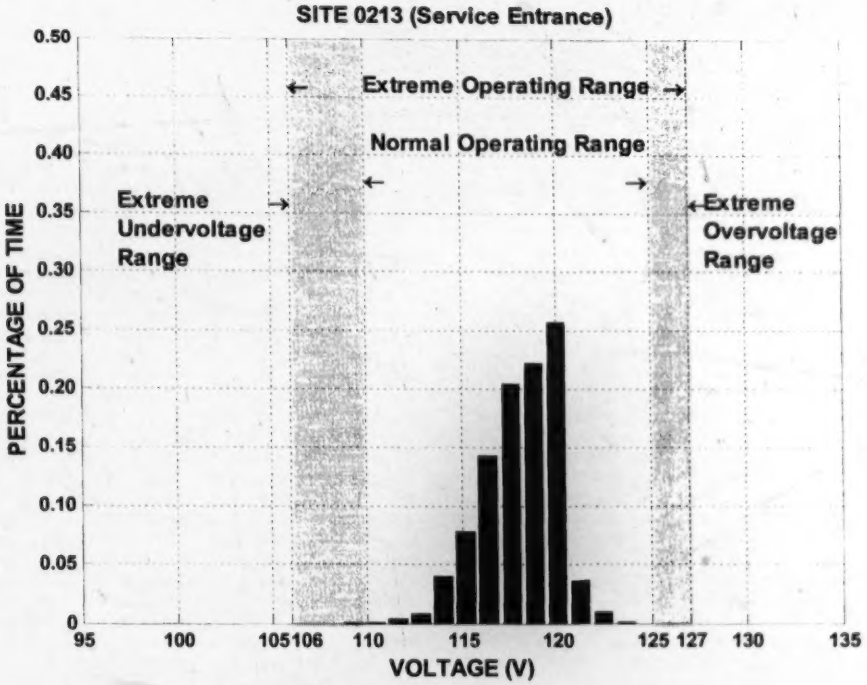

SITE 0167 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

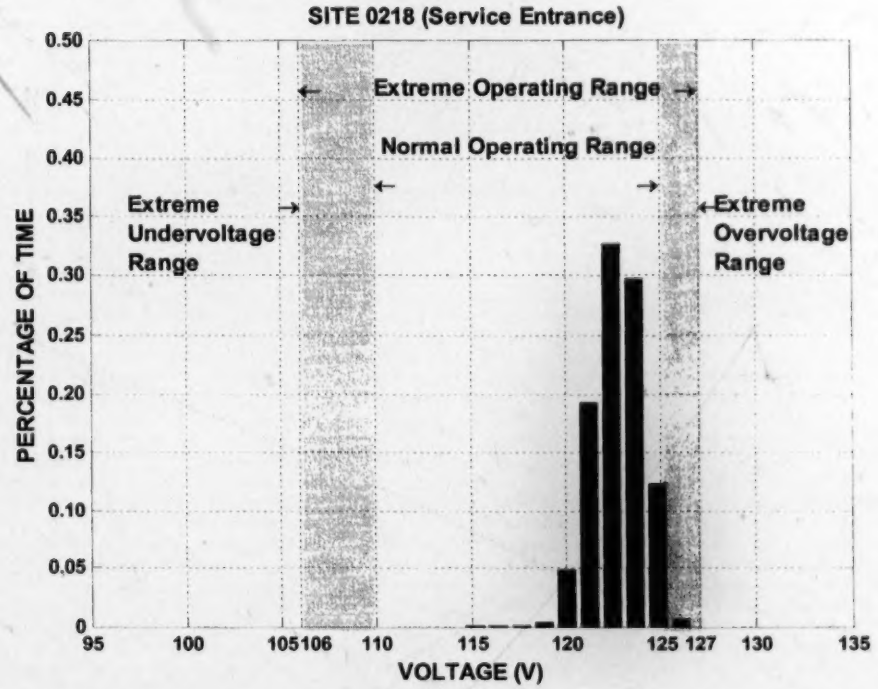

SITE 0168 (Service Entrance)
PERCENTAGE OF TIME
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
95
100
105
106
110
115
120
125
127
130
135
VOLTAGE (V)

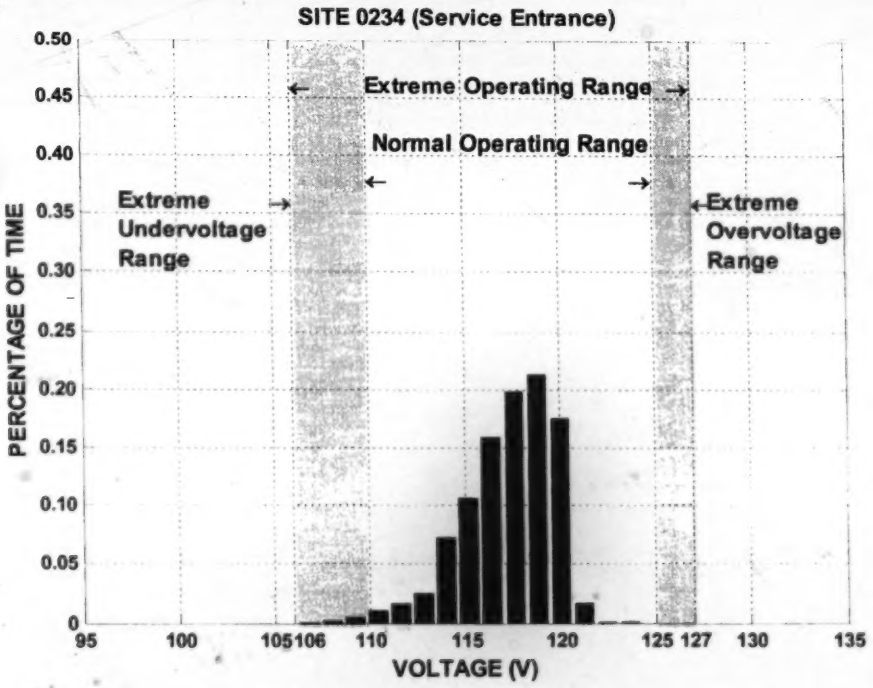

SITE 0169 (Service Entrance)
PERCENTAGE OF TIME
0.6
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.15
0.10
0.05
0
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
95
100
105
106
110
115
120
125
127
130
135
VOLTAGE (V)

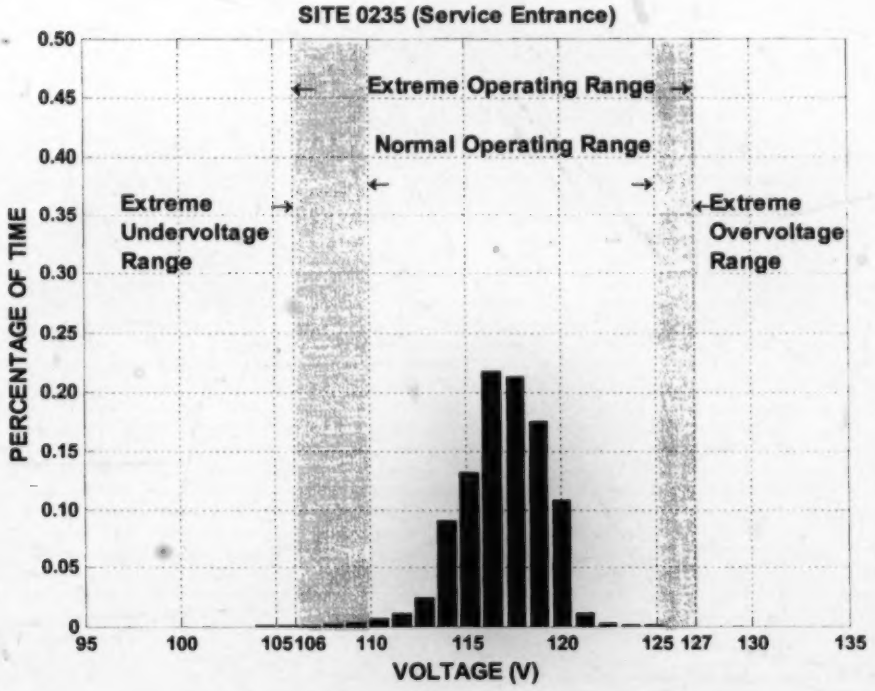

SITE 0175 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

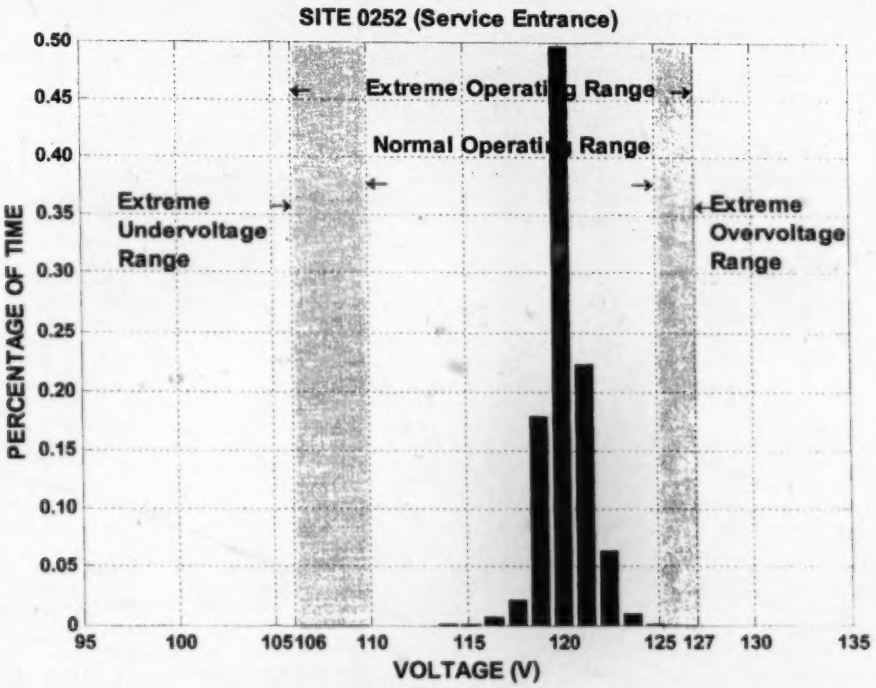

SITE 0206 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

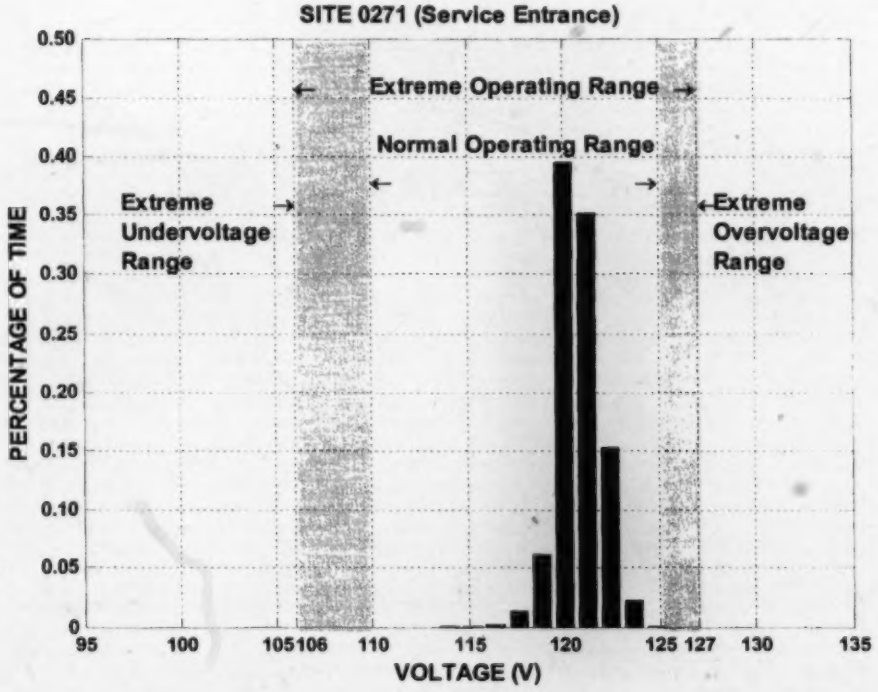

SITE 0213 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

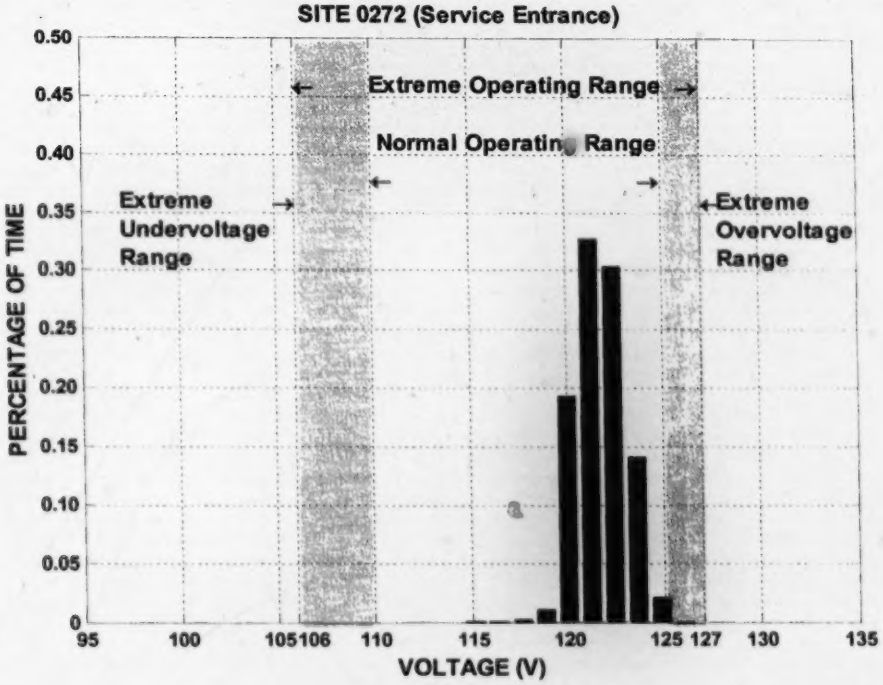

SITE 0218 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

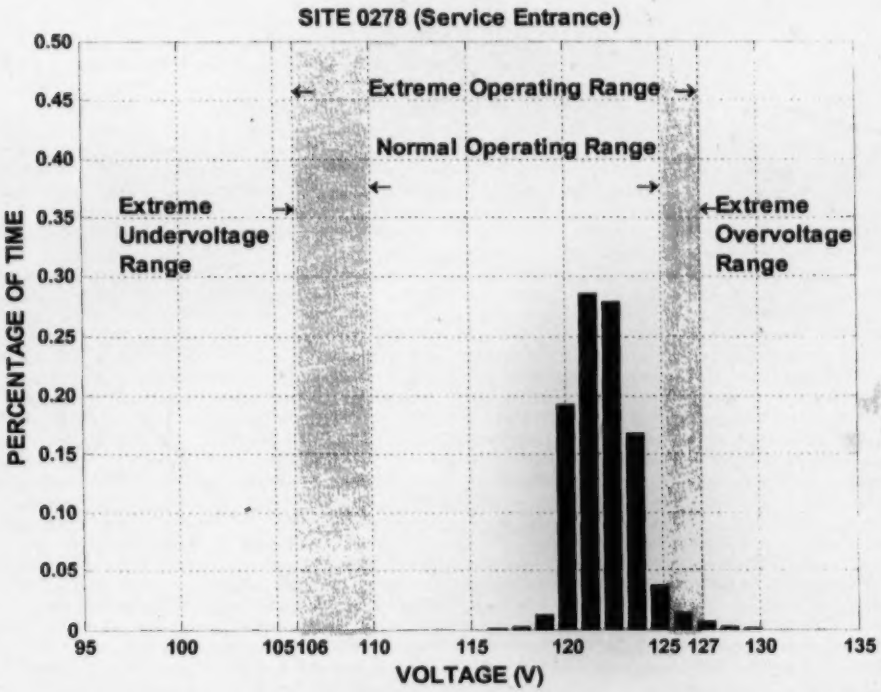

SITE 0234 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

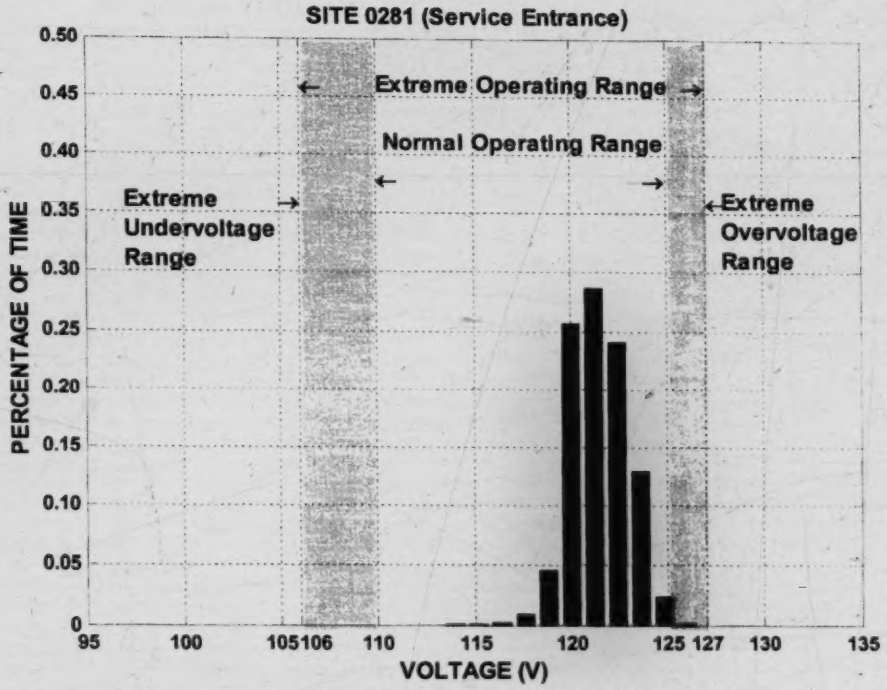

SITE 0235 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

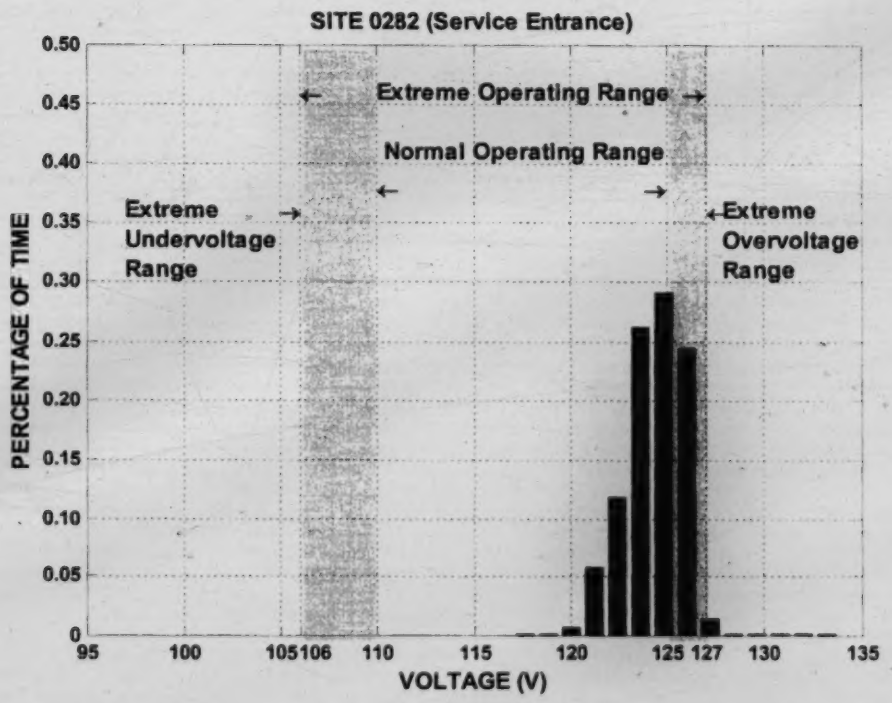

SITE 0252 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

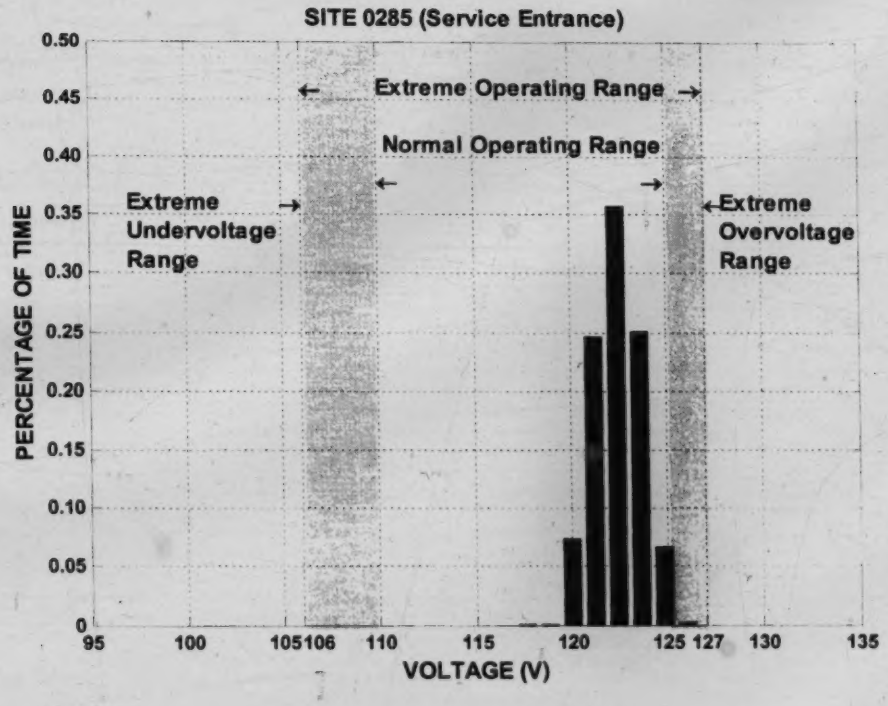

SITE 0271 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

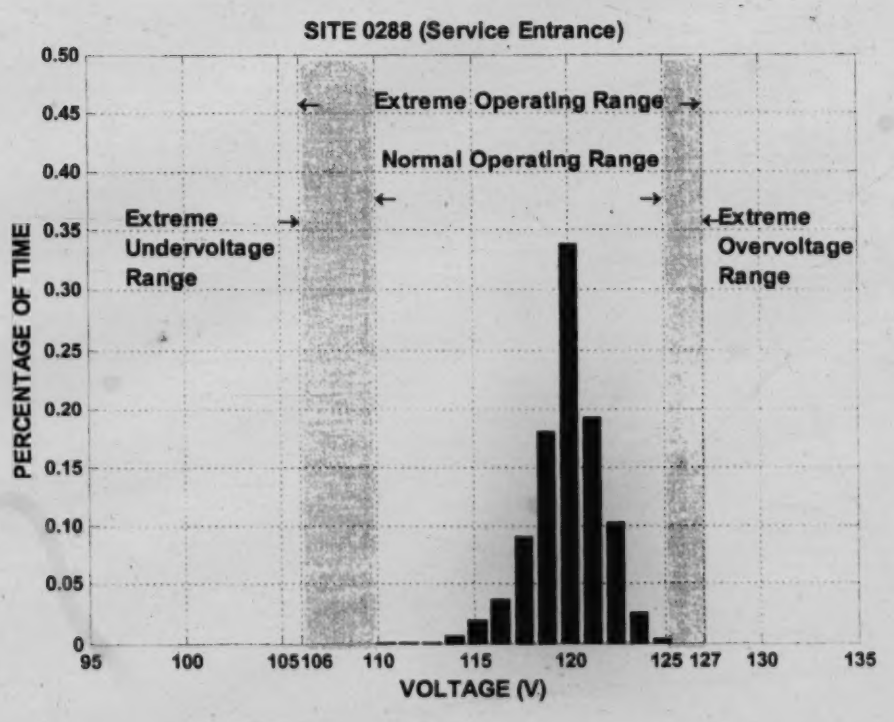

SITE 0272 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

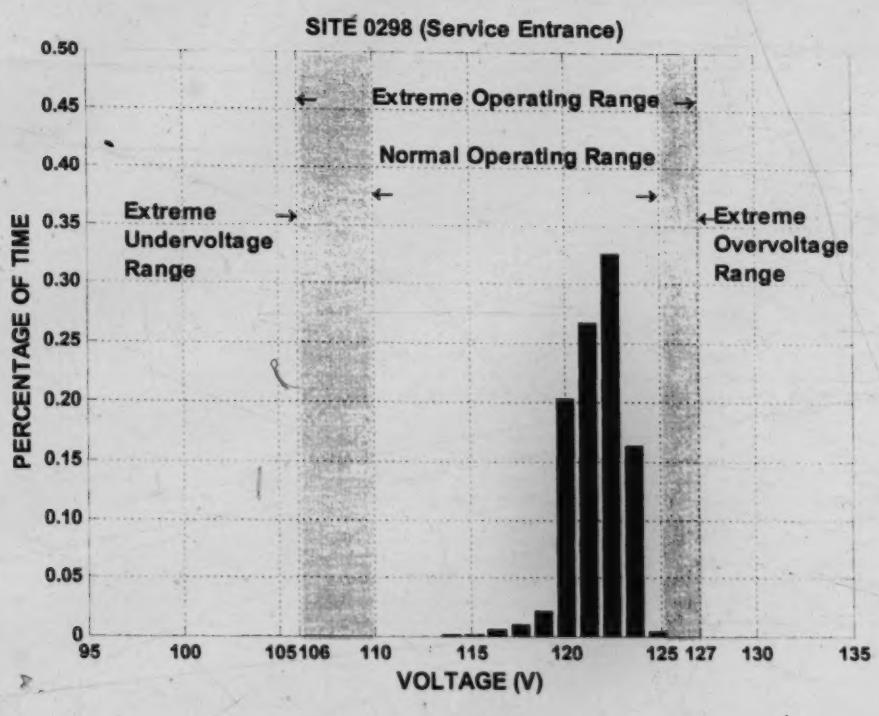

SITE 0278 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

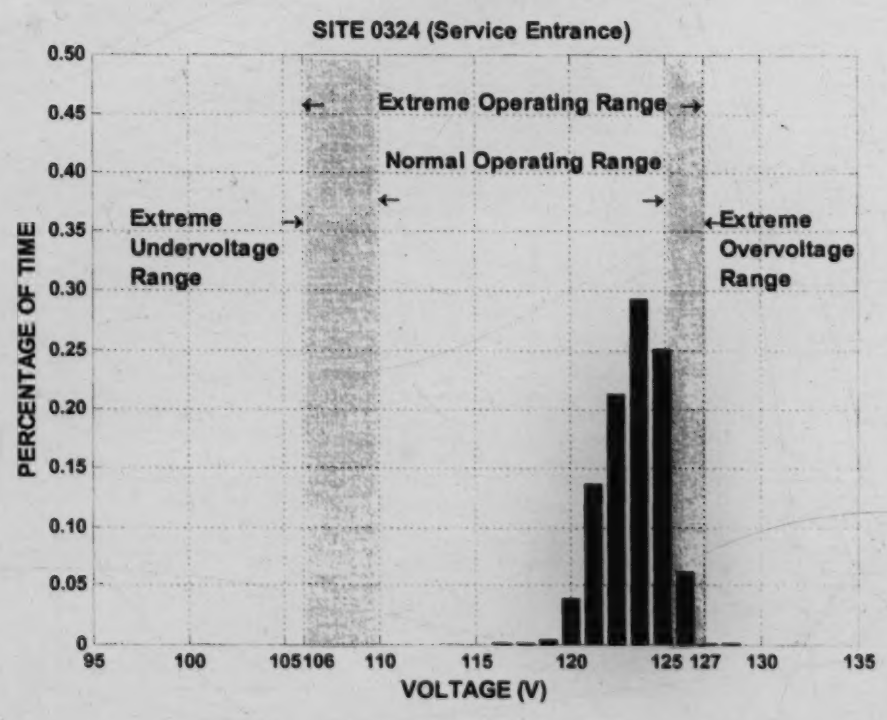

SITE 0281 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

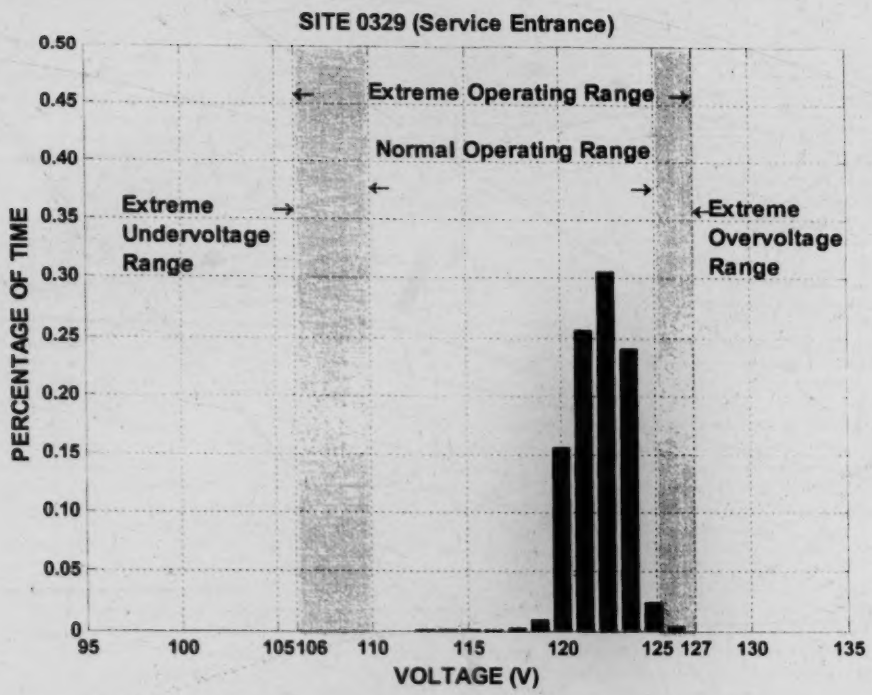

SITE 0282 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

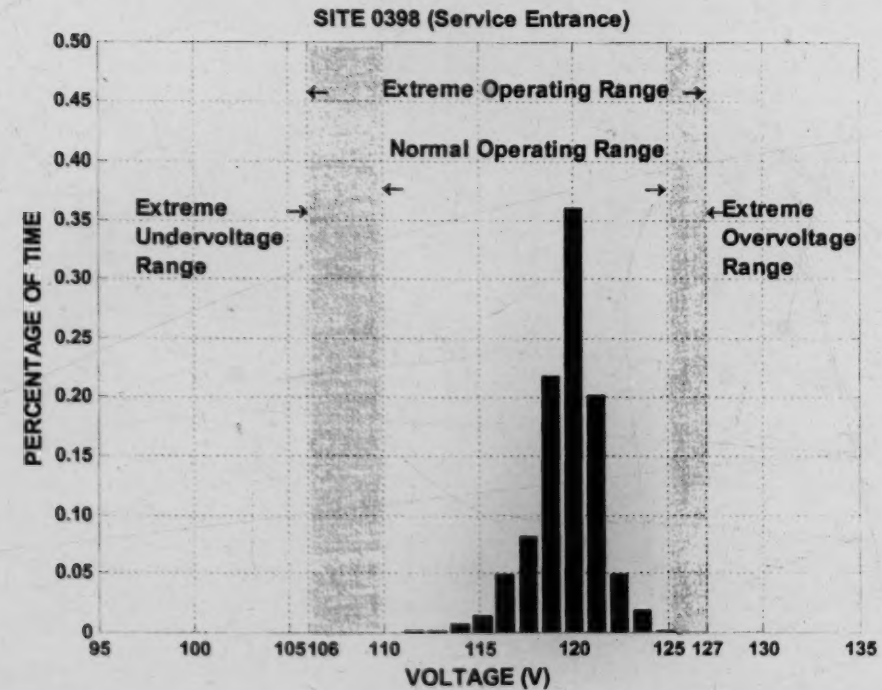

SITE 0285 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

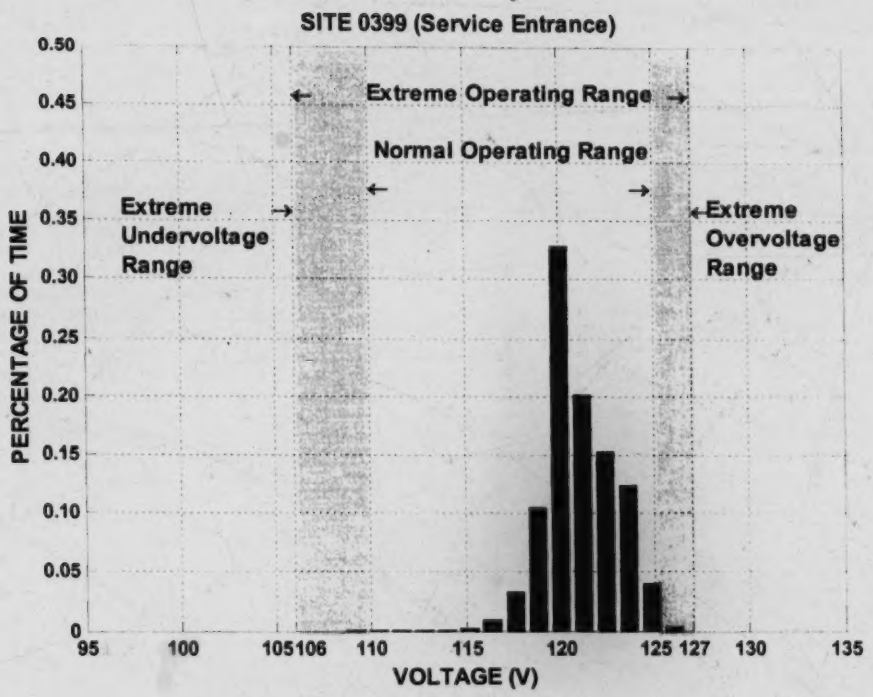

SITE 0288 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

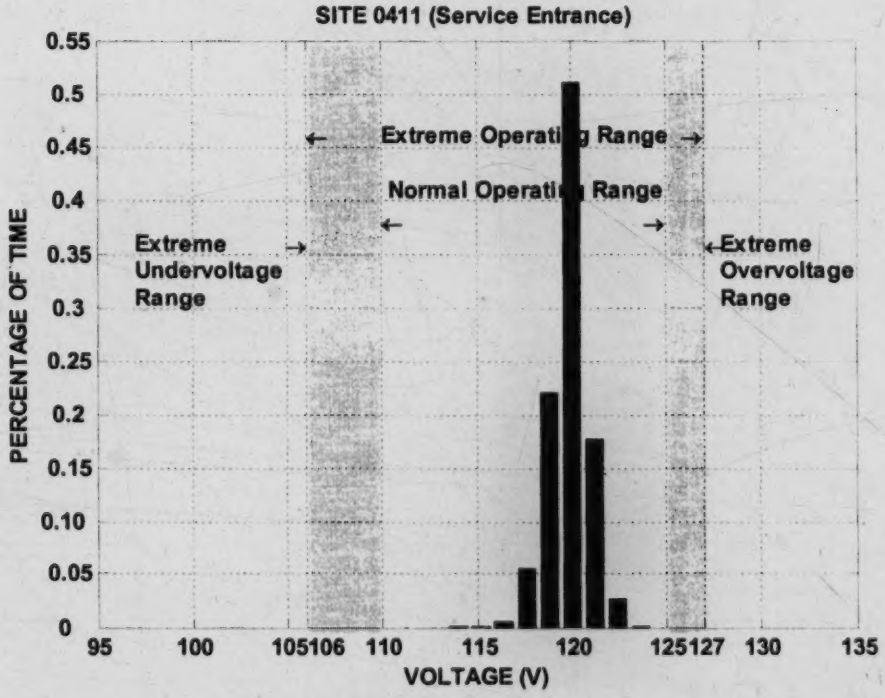

SITE 0298 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

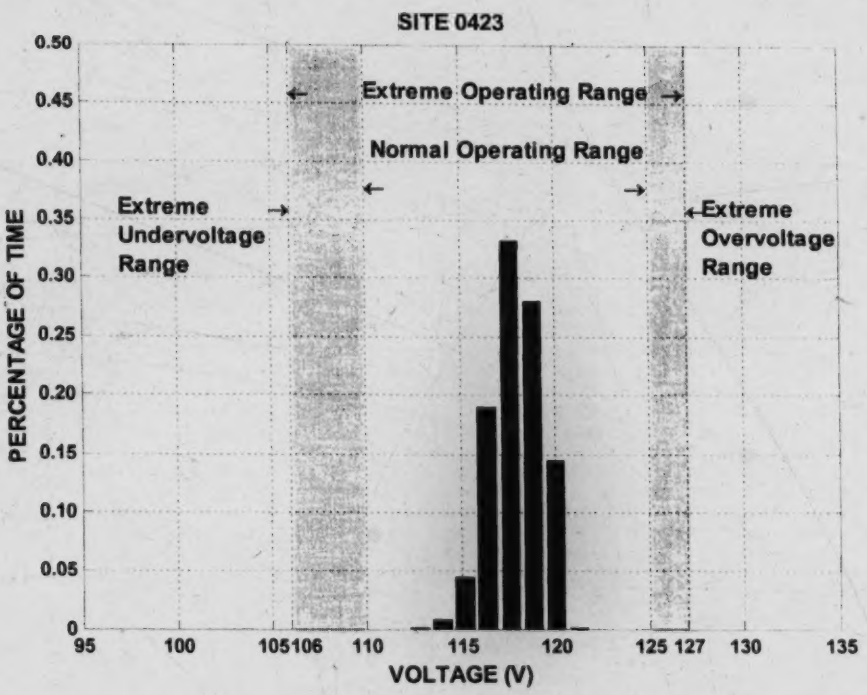

SITE 0324 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

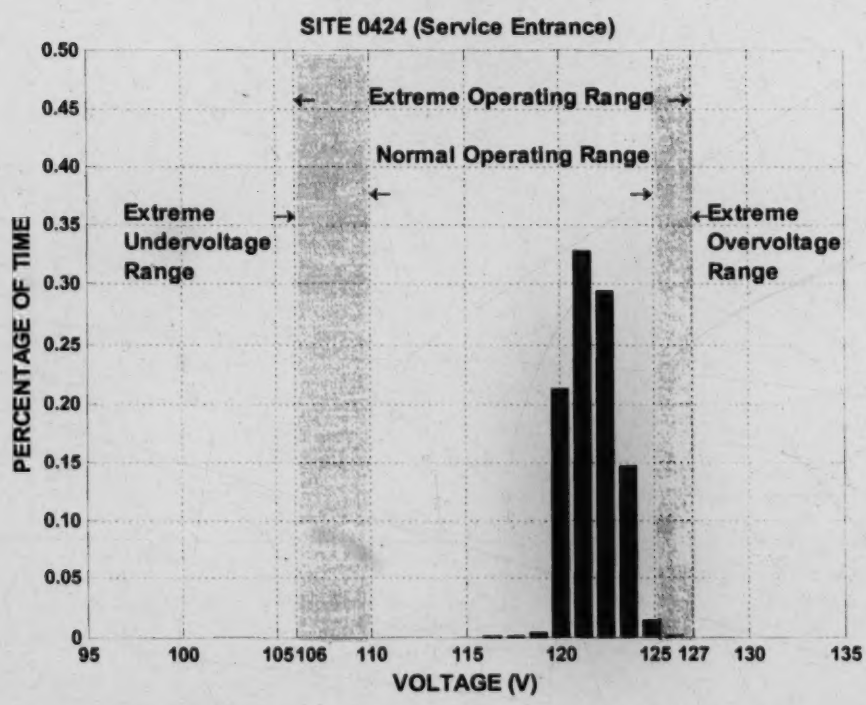

SITE 0329 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

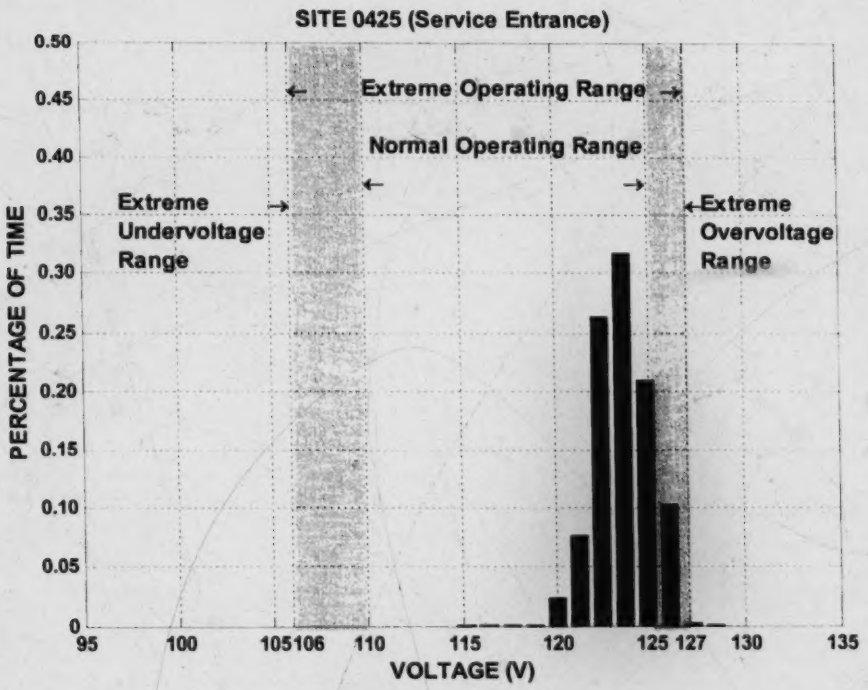

SITE 0398 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

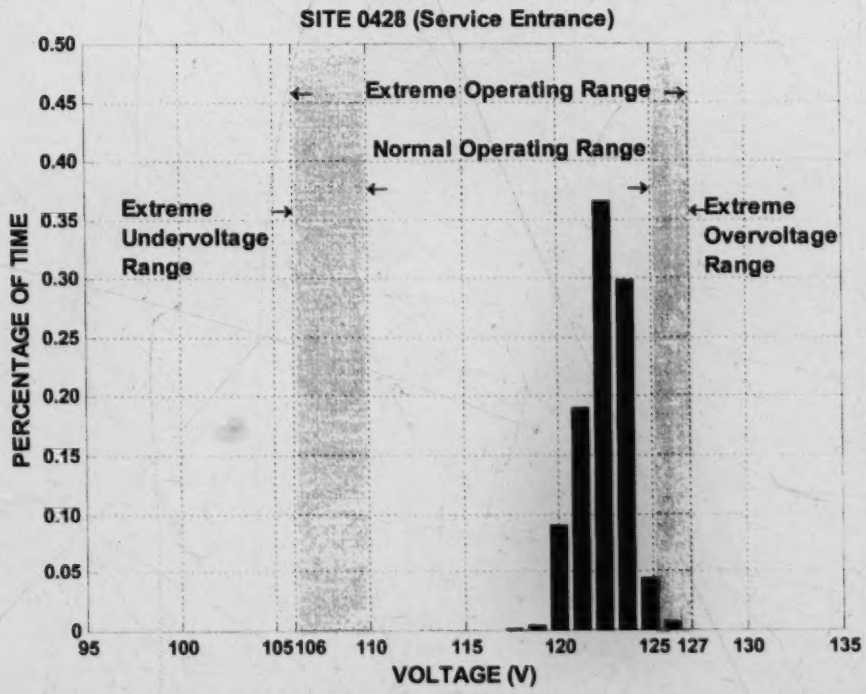

SITE 0399 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

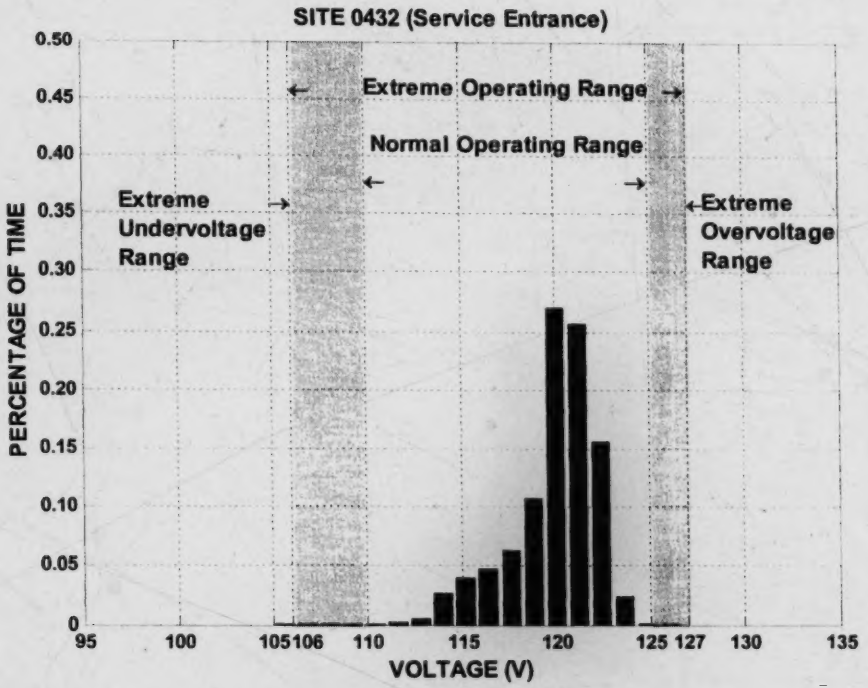

SITE 0411 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

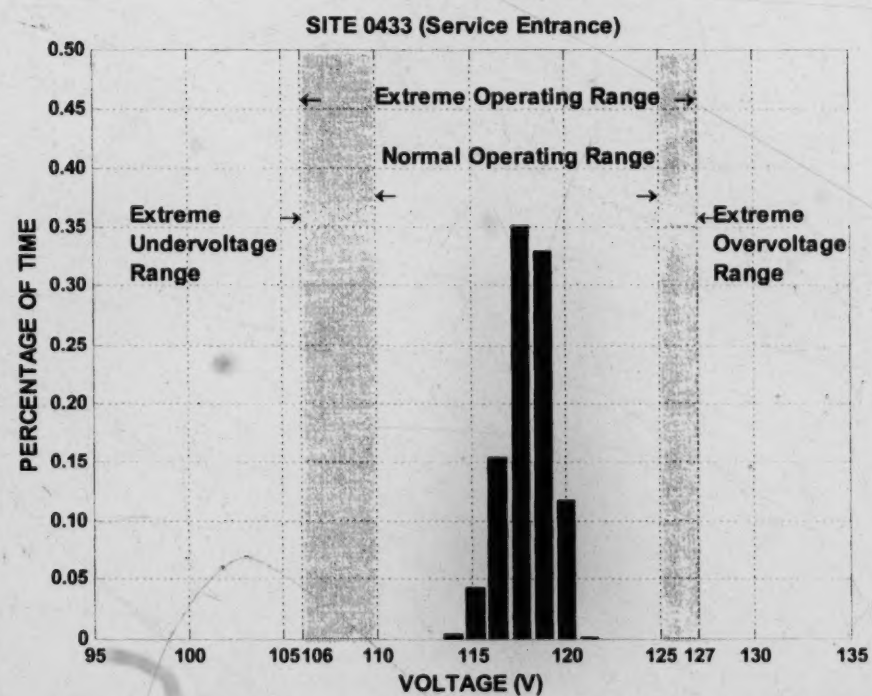

SITE 0423
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135
VOLTAGE (V)

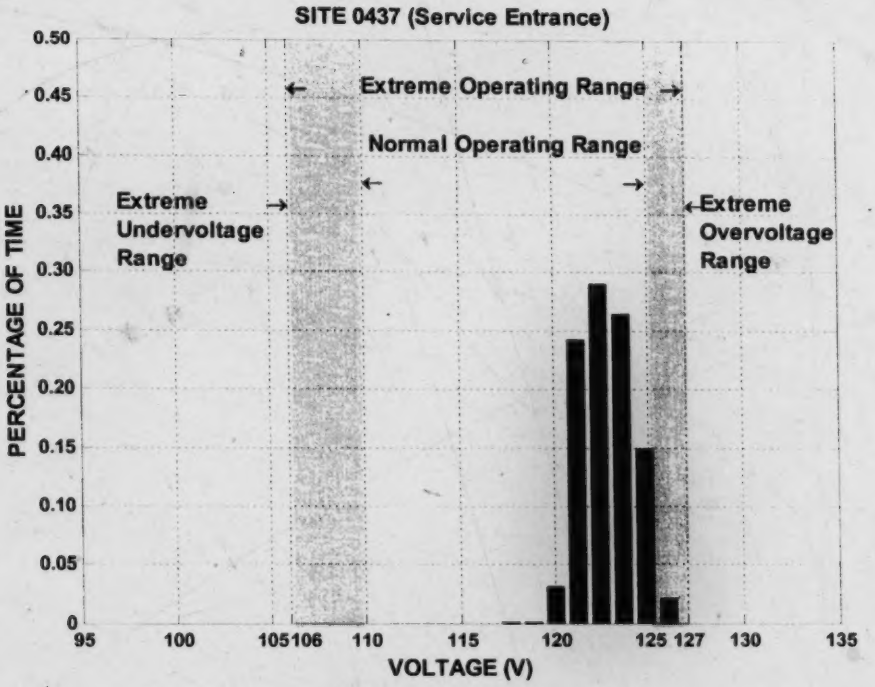

SITE 0424 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135
VOLTAGE (V)

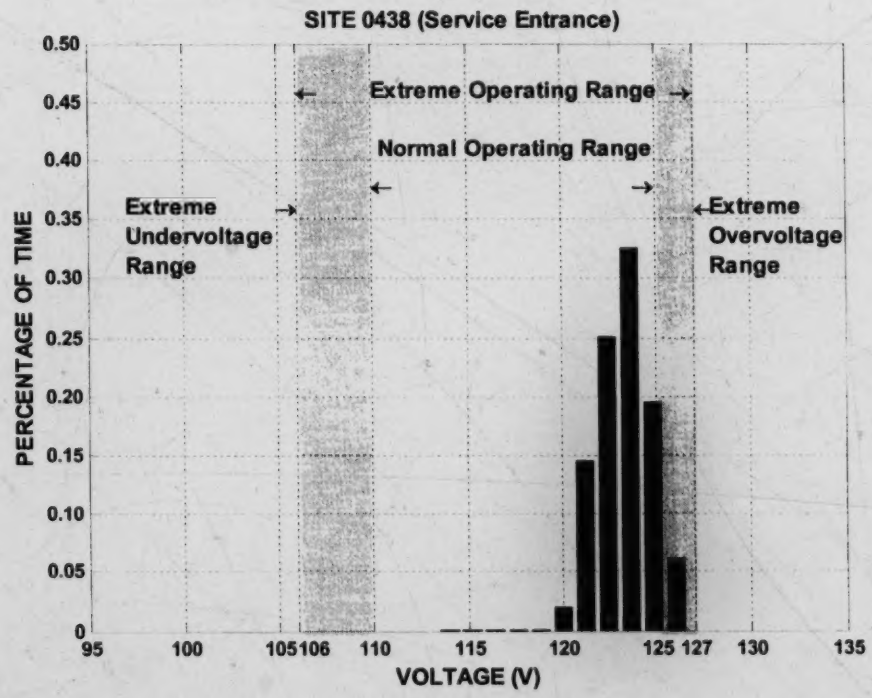

SITE 0425 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135
VOLTAGE (V)

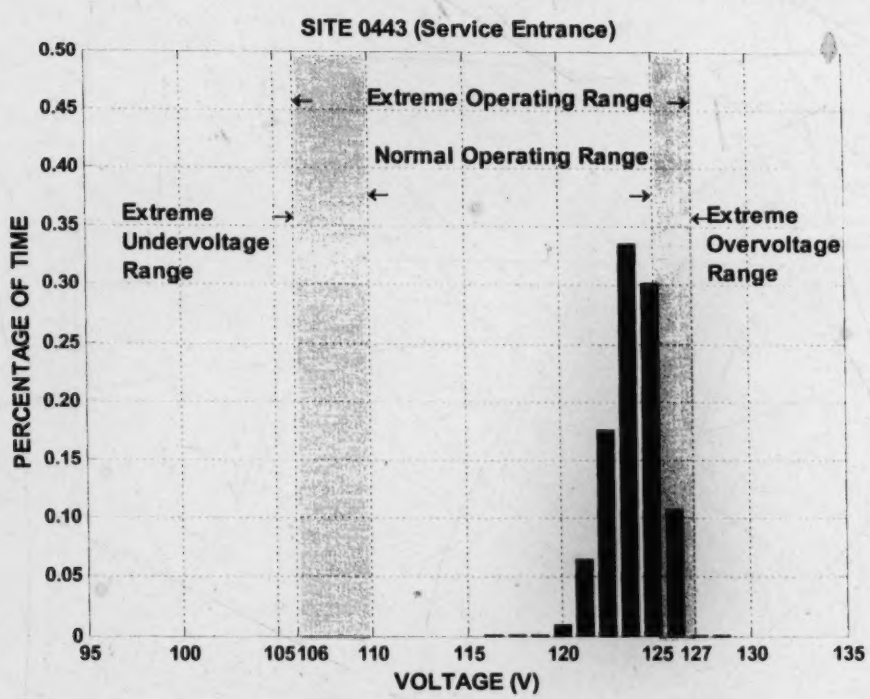

SITE 0428 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135
VOLTAGE (V)

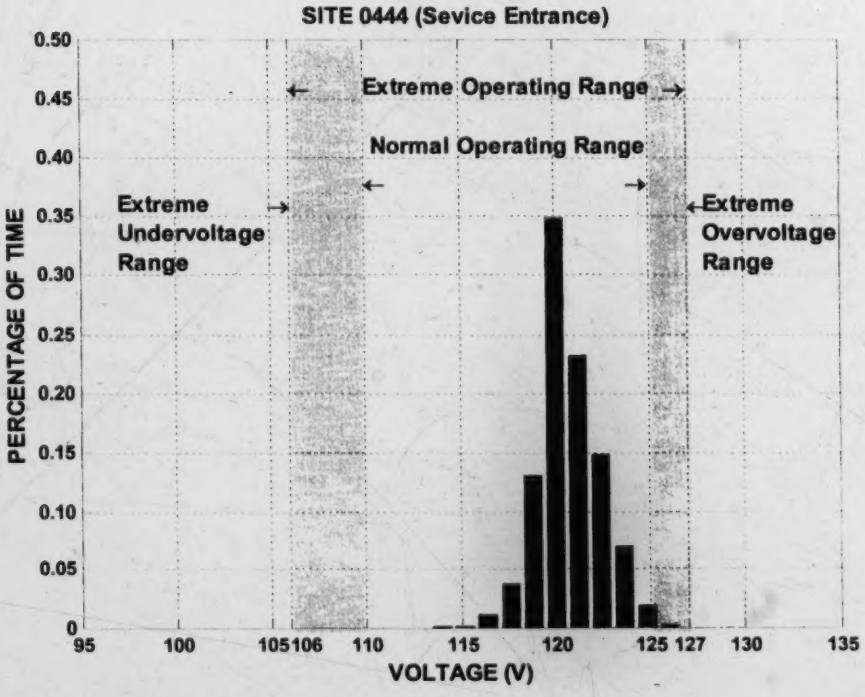

SITE 0432 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135
VOLTAGE (V)

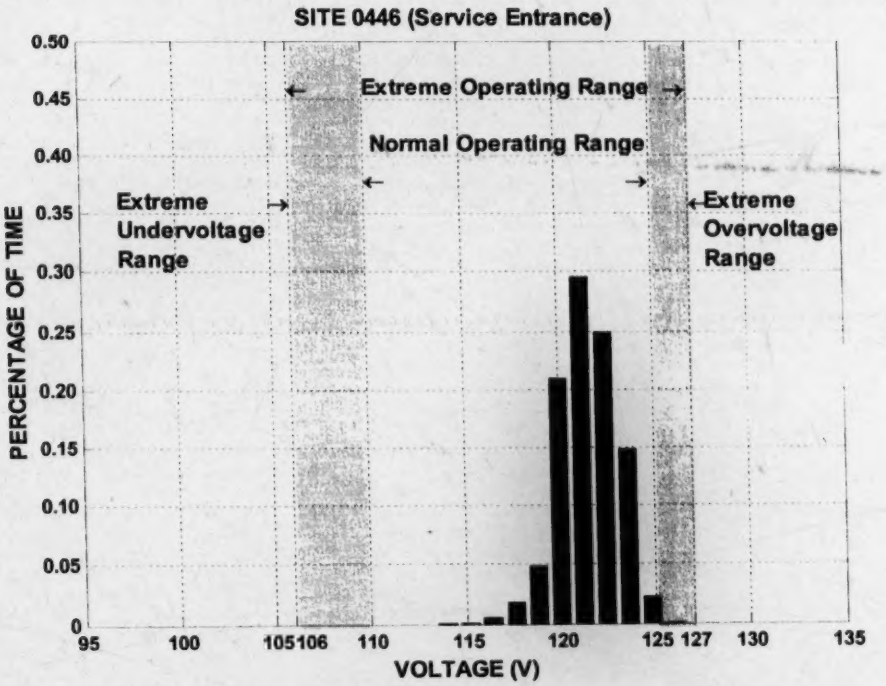

SITE 0433 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135
VOLTAGE (V)

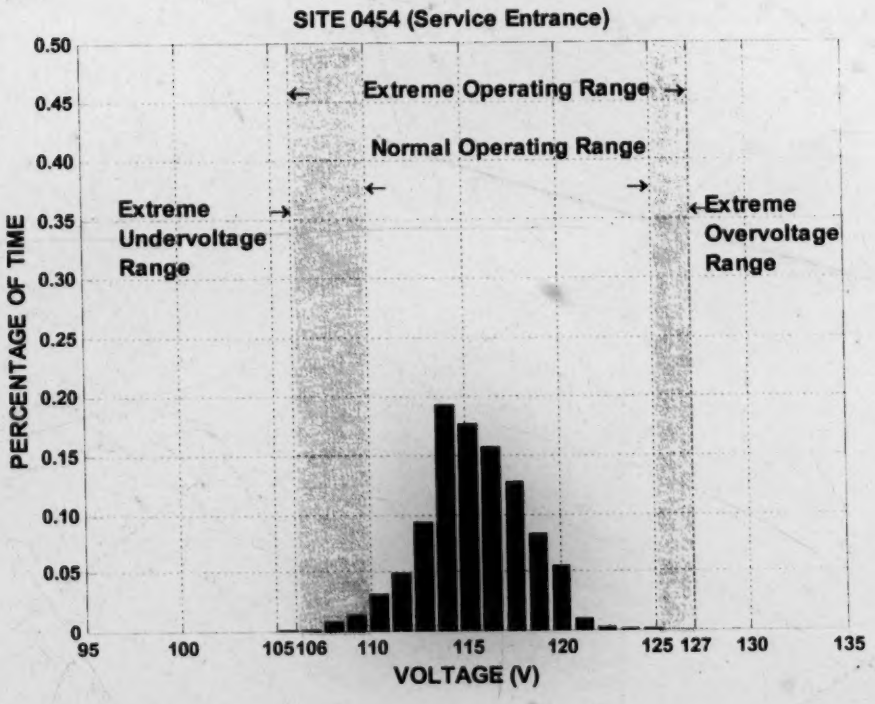

SITE 0437 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

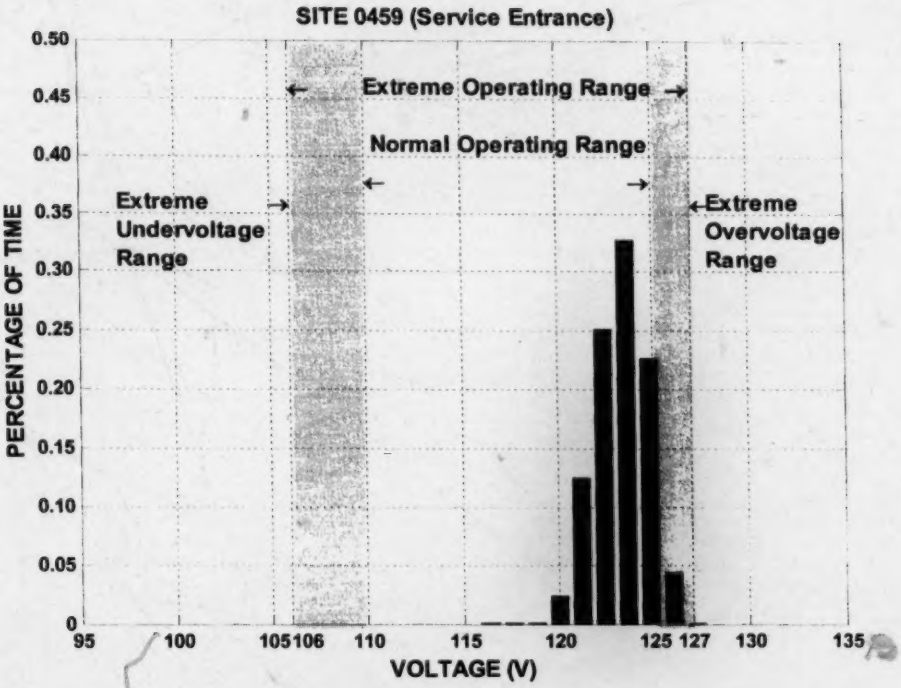

SITE 0438 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

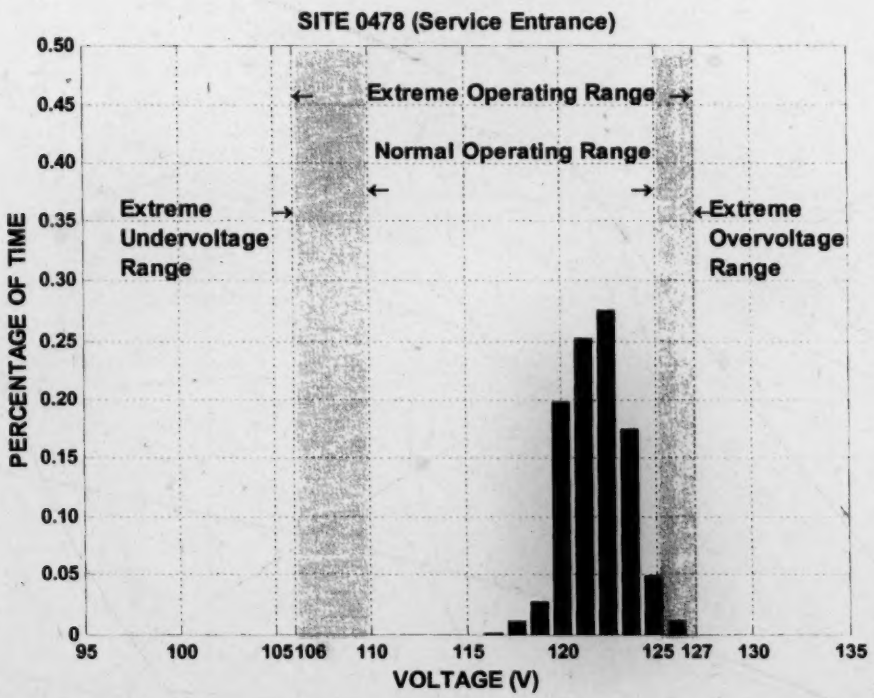

SITE 0443 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

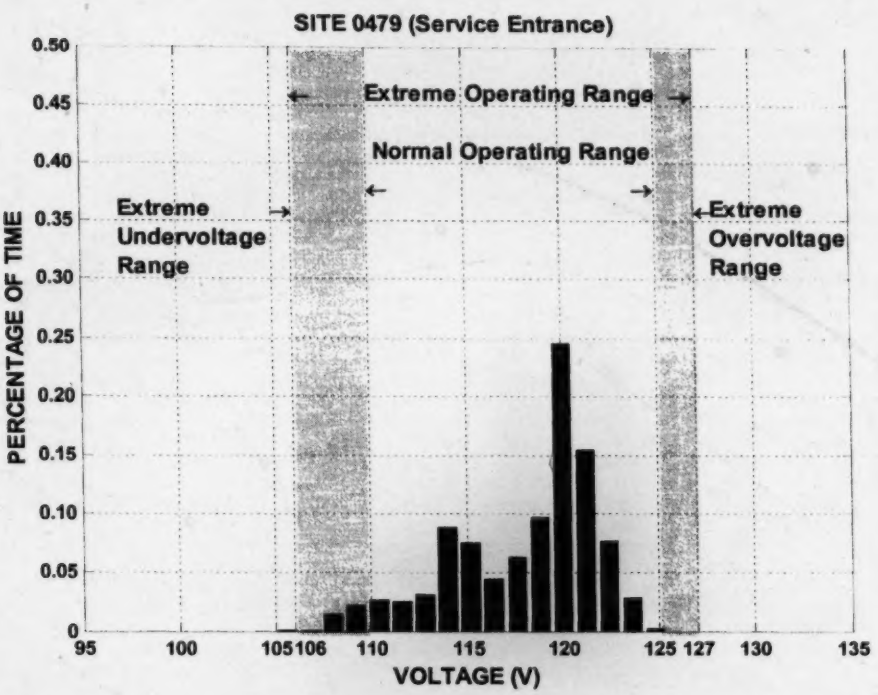

SITE 0444 (Sevice Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

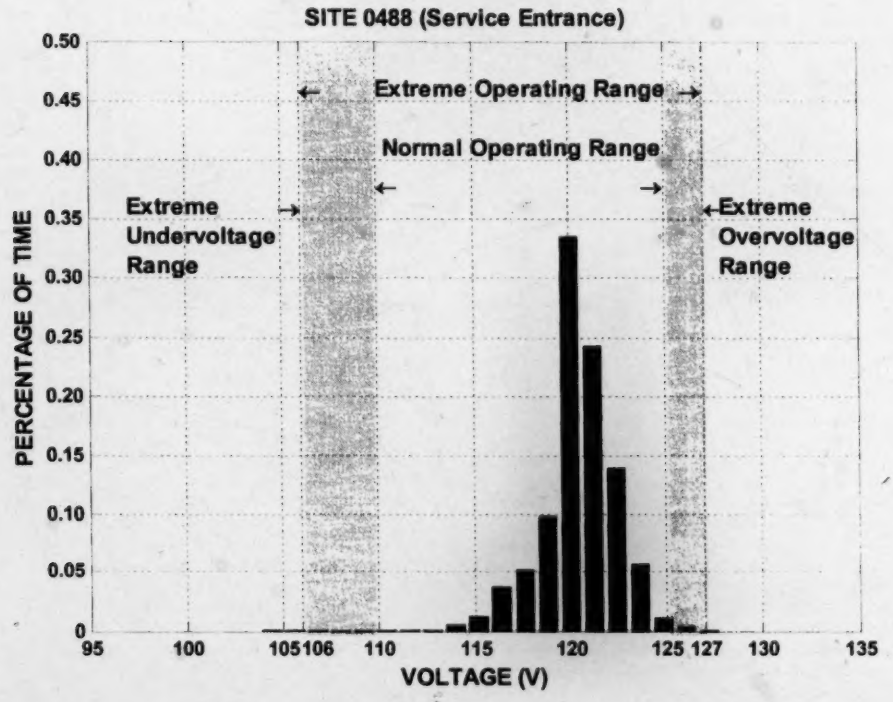

SITE 0446 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

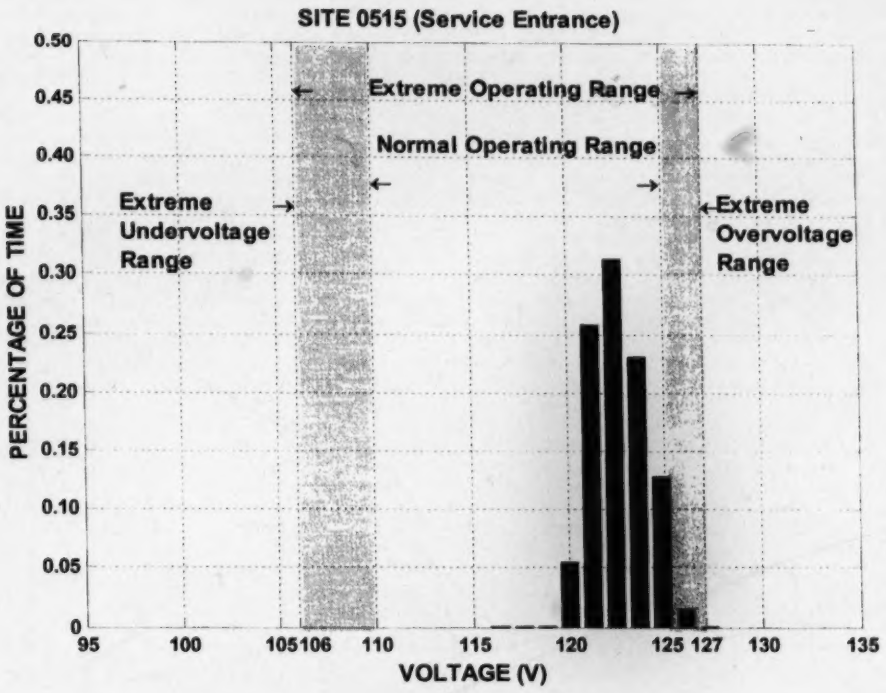

SITE 0454 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

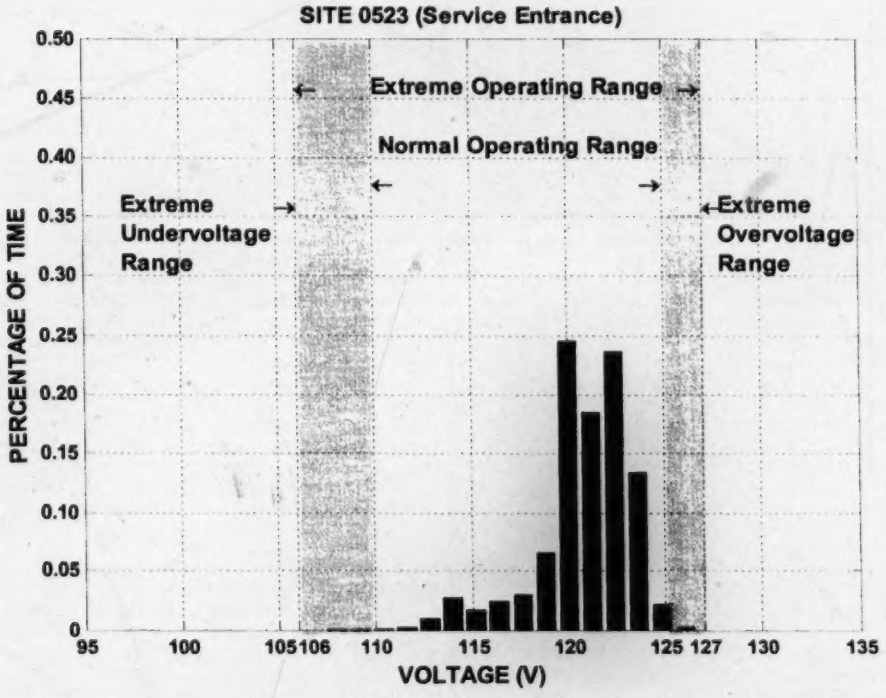

SITE 0459 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135
VOLTAGE (V)

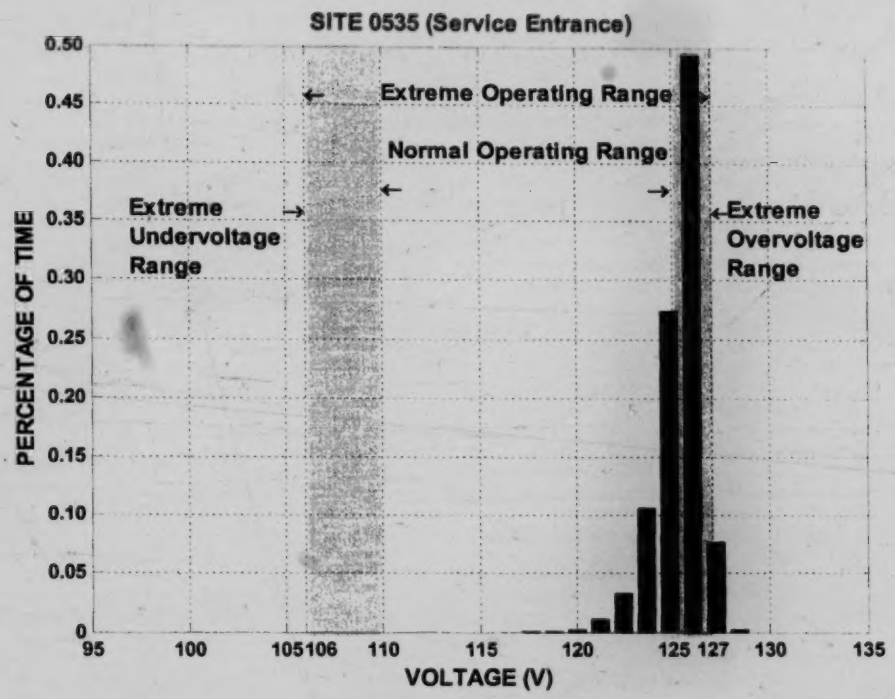

SITE 0478 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135
VOLTAGE (V)

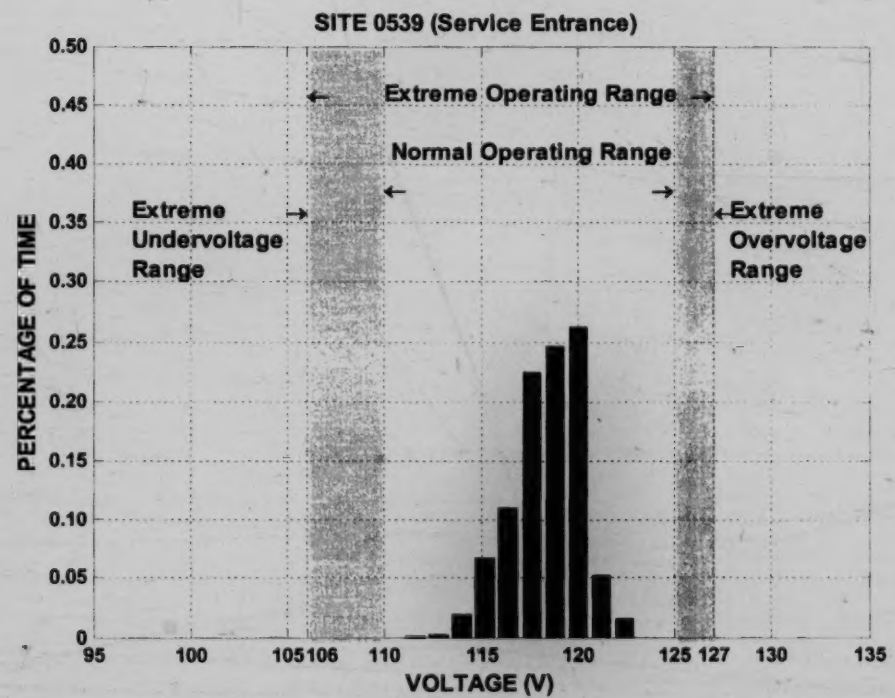

SITE 0479 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

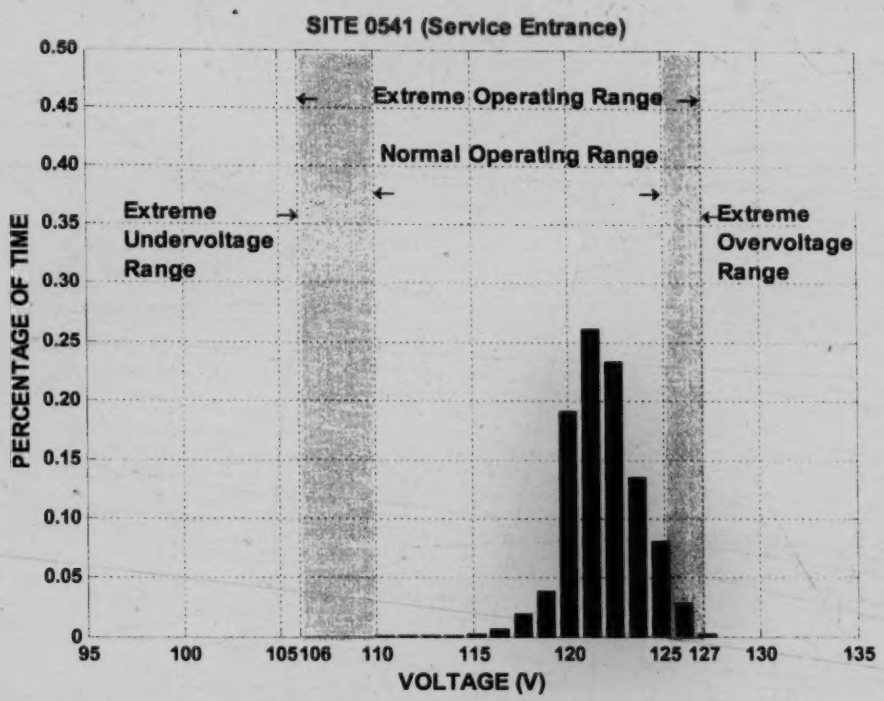

SITE 0488 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

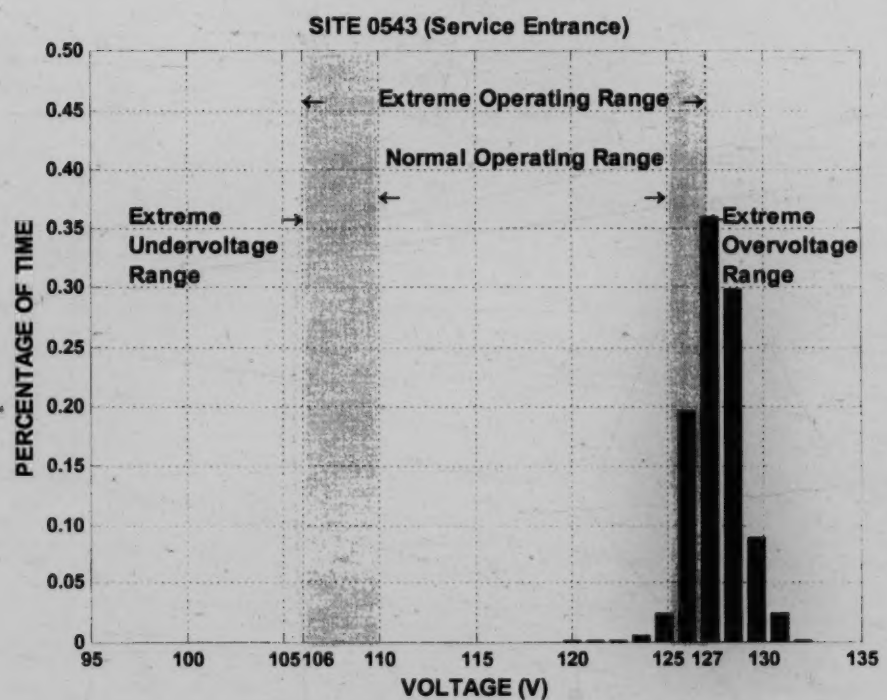

SITE 0515 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

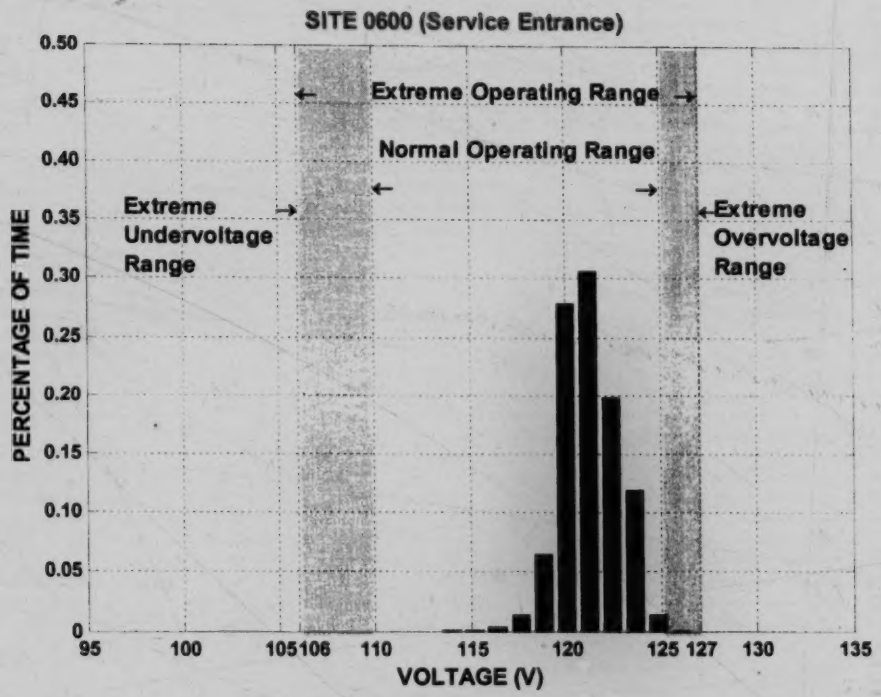

SITE 0523 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

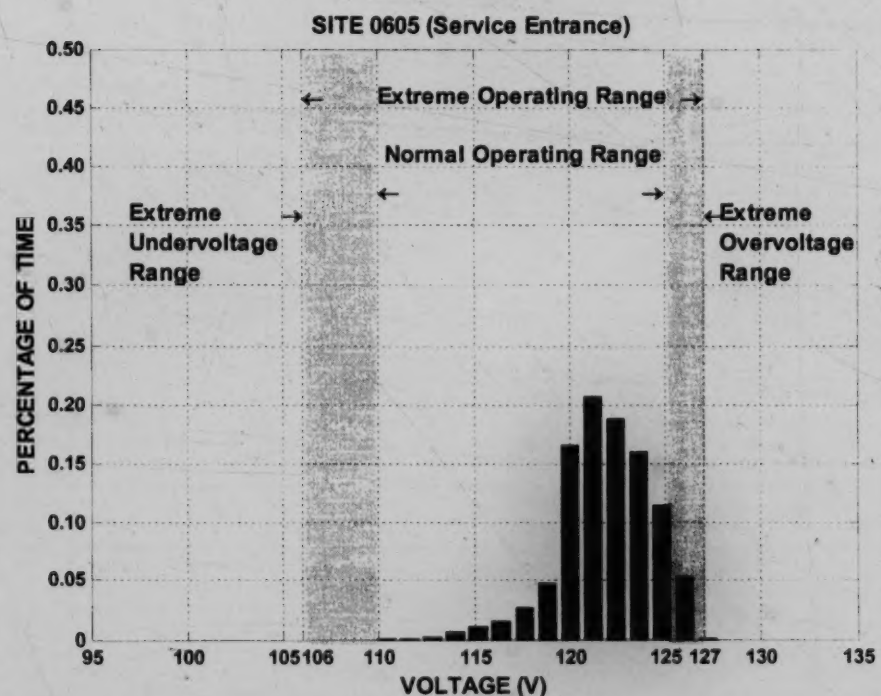

SITE 0535 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

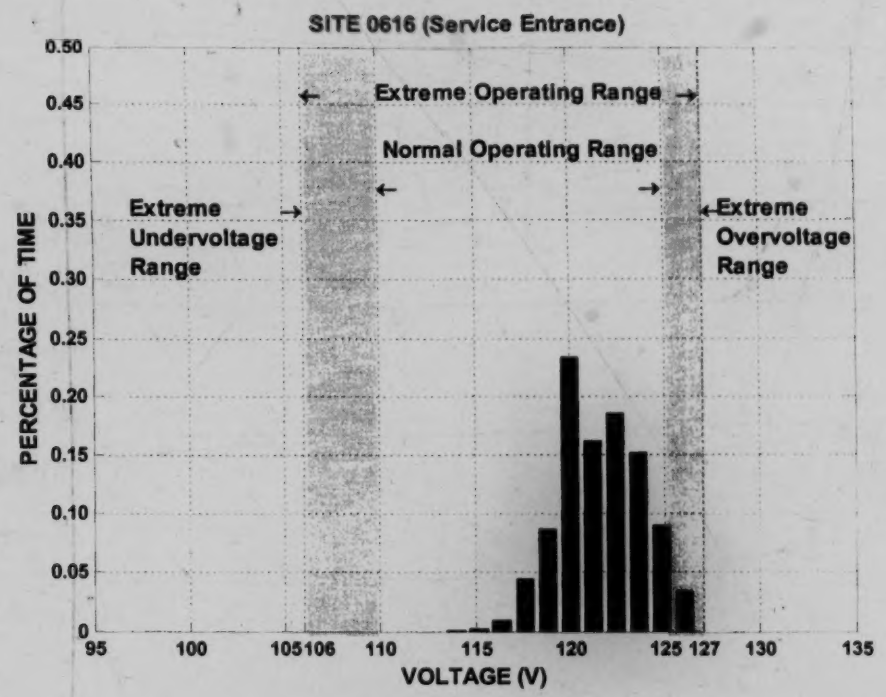

SITE 0539 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

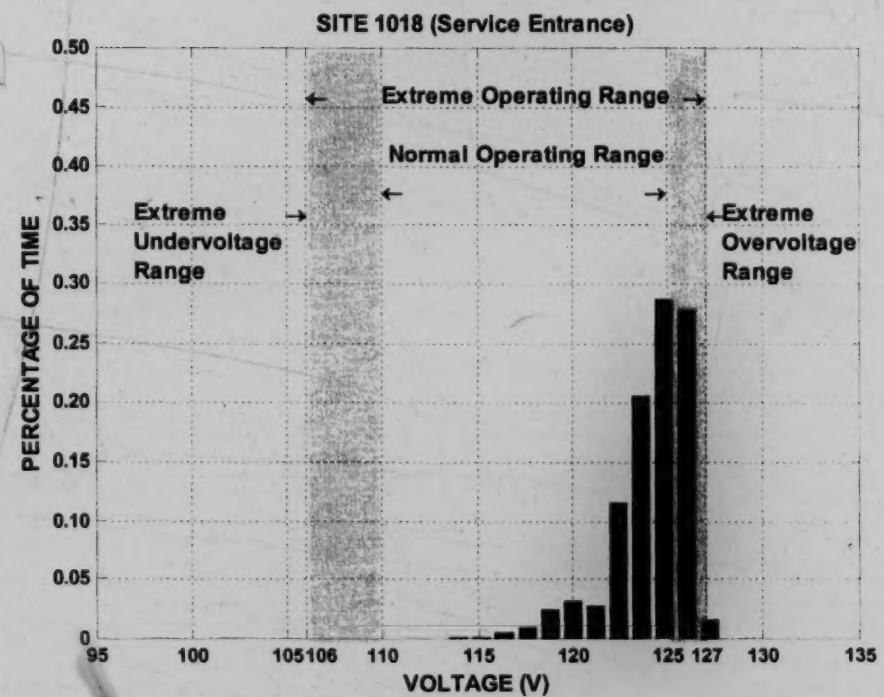

SITE 0541 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

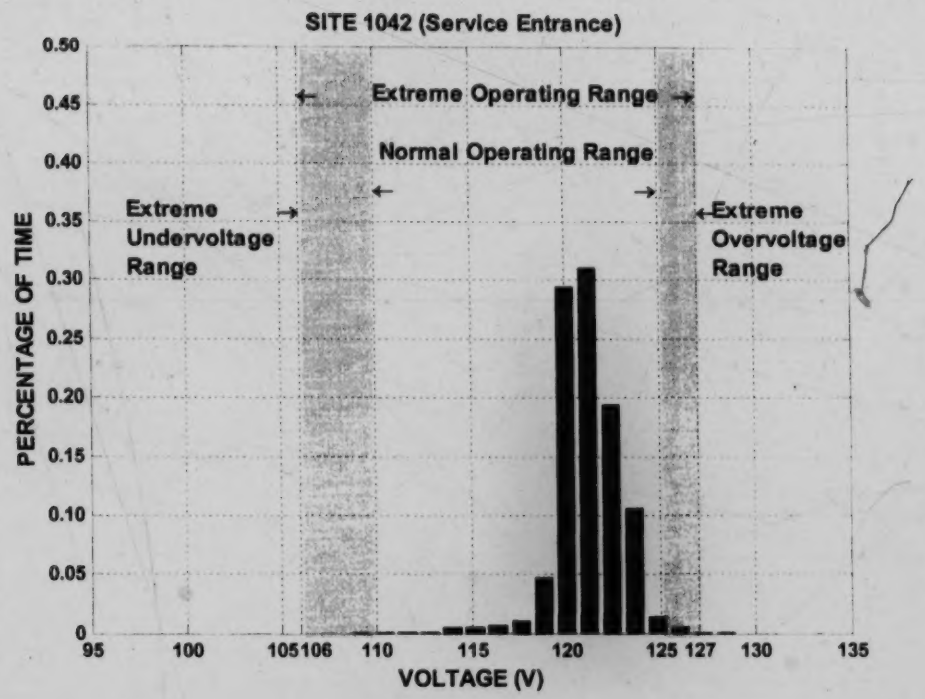

SITE 0543 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135

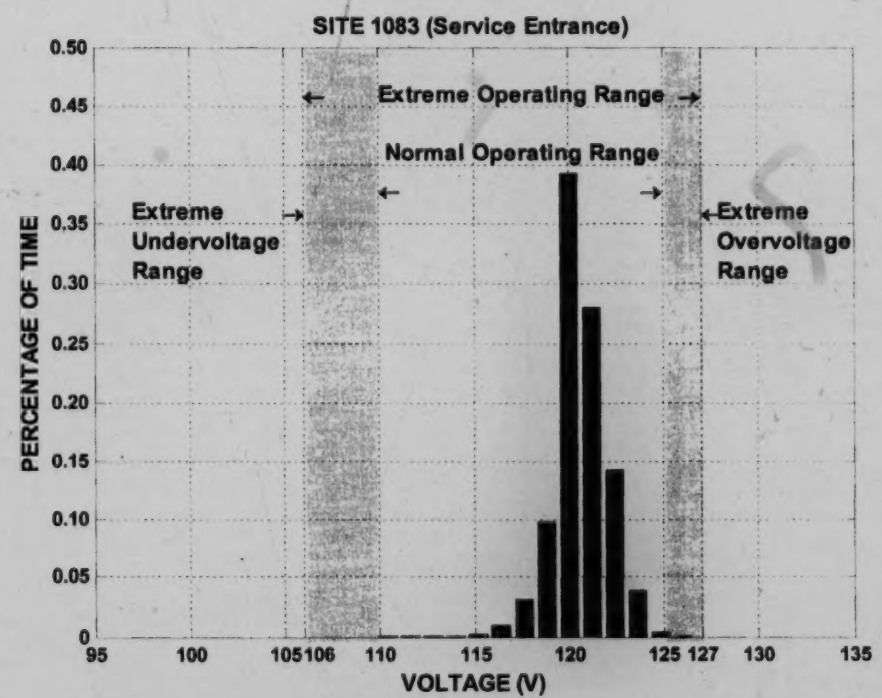

SITE 0600 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135


SITE 0605 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135


SITE 0616 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135


SITE 1018 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135


SITE 1042 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135


SITE 1083 (Service Entrance)
Extreme Operating Range
Normal Operating Range
Extreme Undervoltage Range
Extreme Overvoltage Range
PERCENTAGE OF TIME
VOLTAGE (V)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
95
100
105
106
110
115
120
125
127
130
135